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प्रबलित कंकरीट चिमनी — मापदण्ड

(तीसरा पुनरीक्षण)

Design of Reinforced Concrete Chimneys — Criteria

(Third Revision)

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FOREWORD

This Indian Standard (Third Revision) was adopted by the Bureau of Indian Standards, after the draft finalized by the Special Structures Sectional Committee had been approved by the Civil Engineering Division Council.

This standard was first published in 1968 as IS 4998 and subsequently revised in 1975. The second revision was brought out in 1992, and was intended to be in two parts. Part 1 (published in 1992) dealing with the assessment of loads and the Part 2 envisioned to deal with design criteria for reinforced concrete circular (RC) chimneys.

In this present revision, both the above aspects of assessment of loads and design criteria are consolidated into a single standard. Only chimneys of circular cross-section have been included. For the case of non-circular RC chimneys, specialist advice shall be sought for estimating dynamic wind loads.

The rapid growth of RC chimney construction with a significant increase in capacity, size and height has led to several queries being raised by designers and practising engineers with regard to procedures recommended in IS 4998 (Part 1) : 1992 Criteria for design of reinforced concrete chimneys: Part 1 Assessment of Loads (second revision) for estimation of dynamic wind loads and responses of chimneys. These include,

a) use of simplified method for calculation of across-wind loads;
b) use of discrete strakes as aerodynamic remedial measures for suppressing or alleviating vortex induced oscillations;
c) high values of magnification factors to be used for wind induced interference effects; and
d) incorporation of limit states design.

These aspects are addressed in this standard.

Presently, Boundary Layer Wind Tunnel (BLWT) tests continue to be the reliable design tool for obtaining design inputs of tall chimneys. It is recommended to determine the enhancement/shielding of structural response, if any, due to presence of important surrounding structures which affect the aerodynamics of the flow considerably, BLWT tests on models of tall chimneys be carried out for investigating interference effects.

Assistance has been made to the following documents in formulating this standard:

ACI Committee 307-08, (2008), 'Code Requirements for Reinforced Concrete Chimneys (ACI 307-08) and Commentary', American Concrete Institute, USA.

CICIND, (2001), 'Model Code for Concrete Chimneys – Part A: The Shell (Second edition, Revision 1)', Zurich, Switzerland.

CICIND, (2005), 'Chimney Book – Industrial Chimneys of Concrete or Steel', Zurich, Switzerland.

Devdas Menon and Srinivasa Rao, P., (1998), 'Reliability of Wind Resistant Design of Tubular Reinforced Concrete Towers', Journal of Structural Engineering, SERC, 25, 21-29.

Devdas Menon, (1998), 'Moment-Curvature Relationships to Estimate Deflections and Second-Order Moments in Wind-loaded RC Chimneys and Towers', Wind and Structures, 1, 255-269.

Lakshmanan, N. Arunachalam, S., Selvi Rajan, S., Ramesh Babu, G., (2007), 'Some Considerations on the Specifications of the Indian Standard on Wind Loads IS : 875 (Part 3) – 1987', Proceedings of the 4th National Conference on Wind Engineering, Chennai, 75-84.

Rao, G.N.V., (1985), 'Wind Effects on Tall Chimneys', Asia Pacific Symposium on Wind Engineering, December, University of Roorkee, India.

ESDU 96030, (1996), 'Response of Structures to Vortex Shedding - Structures of Circular or Polygonal Cross Section', ESDU, UK.

Riera, J.D. and Davenport, A.G., (1998), 'Wind Effects on Buildings and Structures', Balkema, Rotterdam.

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Indian Standard

DESIGN OF REINFORCED CONCRETE CHIMNEYS — CRITERIA

(Third Revision)

1 SCOPE

This standard deals with materials, design and construction requirements for industrial reinforced concrete chimneys. The standard provides recommendations on assessment of various loadings, and methods to compute stresses in concrete and steel due to these loadings. This standard is valid for reinforced concrete chimneys of circular cross-section.

2 REFERENCES

The standards listed in Annex A contain provision which through reference in this text, constitute provisions of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision and parties to agreement based on this standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated therein.

3 SYMBOLS AND NOTATIONS

B = background factor indicating the slowly varying component of along-wind load fluctuations

B_w = band-width parameter

$\bar{C}_D$ = mean drag coefficient of the chimney

C_E = end-effect factor

C_L = RMS lift coefficient

C_{Lo} = RMS lift coefficient modified for local turbulence

C_b = coefficient of thermal conductivity of chimney uninsulated lining or insulation around steel liner, to be obtained from the manufacturer of the materials used [Watt / (m Kelvin)]

C_c = coefficient of thermal conductivity of concrete of chimney shell [Watt / (m Kelvin)]

C_s = coefficient of thermal conductivity of insulation filling in space between lining and shell, to be obtained from the manufacturer of the materials used [Watt / (m Kelvin)]

C_{sf} = short-term loading factor

c = ratio of distance from extreme compression fibre to neutral axis for vertical stresses to total thickness (t)

c' = ratio of distance from extreme compression fibre to neutral axis for circumferential stresses to total thickness (t)

d_H = centerline diameter of the shell at top (m)

$d(z)$ = outer diameter of chimney at height z (m)

d_e = effective diameter taken as average outer diameter over top one-third height of chimney (m)

d_o = centerline diameter of the shell at bottom (m)

d_b = centerline diameter of uninsulated lining or insulation around liner (m)

d_{bi} = inside diameter of uninsulated lining or insulation around liner (m)

d_c = centerline diameter of concrete chimney shell (m)

d_{ci} = inside diameter of concrete chimney shell (m)

d_{co} = outside diameter of concrete chimney shell (m)

d_s = centerline diameter of space between lining and shell (m)

E = measure of the available energy in the wind at the natural frequency of chimney

E_{ck} = dynamic modulus of elasticity of concrete (N/m^2)

e = distance between central line of the shell and the centre of gravity of the local load, m

E_c = Modulus of elasticity of concrete (N/mm^2)

E_s = Modulus of elasticity of steel (N/mm^2)

F_{1A} = Strouhal number parameter

F_{1B} = lift coefficient parameter

$F(z)$ = along-wind load per unit height at any level, z (N/m)

$F_{ac}(z)$ = across-wind load per unit height at any level, z (N/m)

$\bar{F}_{al}(z)$ = mean along-wind load per unit height at any level, z, corresponding to $\bar{V}_*$ (N/m)

$\bar{F}(z)$ = mean along-wind load per unit height at any level, z, corresponding to $\bar{V}(z)$ (N/m)

$F'(z)$ = fluctuating component of along-wind load per unit height at any level, z (N/m)

f_1 = natural frequency of the chimney in the first mode of vibration (Hz)

f_i = natural frequency of the chimney in the ith mode of vibration (Hz)

f_c = stress in concrete in the chimney cross-section (N/mm^2)

f_s = stress in steel in the chimney cross-section (N/mm^2)

f'_{CTC} = maximum circumferential stress due to temperature in concrete occurring at the inside of the chimney shell (N/mm^2)

f'_{CTV} = maximum vertical stress due to temperature in concrete occurring at the inside of the chimney shell (N/mm^2)

f_{STC} = maximum circumferential stress due to temperature in steel occurring at the outside of the chimney shell (N/mm^2)

f_{STV} = maximum vertical stress due to temperature in steel occurring at the outside of the chimney shell (N/mm^2)

f'_{STV} = maximum vertical stress due to temperature in steel occurring at the inside of the chimney shell (N/mm^2)

f_{ck} = characteristic cube compressive strength of concrete (N/mm^2)

f'_{ck} = modified characteristic cube compressive strength of concrete for temperature effects (N/mm^2)

f_y = characteristic strength of steel (N/mm^2)

f'_y = modified characteristic strength of steel for temperature effects (N/mm^2)

G = gust response factor

$G_r(z)$ = gust factor for radial wind pressure at height z

g_f = peak factor defined as the ratio of the expected peak value to the RMS value of the fluctuating load

g_{ac} = across-wind peaking factor

H = Total height of chimney above ground level (m)

I_{ref} = local turbulence parameter

K_a = aerodynamic damping parameter

K_{ao} = mass damping parameter of small amplitudes

K_i = coefficient of heat transmission from gas to inner surface of chimney lining when chimney is lined, or to inner surface of chimney shell when chimney is unlined [Watt/(m^2 Kelvin)] (*see* Fig. 1).

K_o = coefficient of heat transmission from outside surface of chimney shell to surrounding air [Watt/(m^2 Kelvin)]

K_r = coefficient of heat transfer by radiation between outside surface of lining and inside surface of concrete chimney shell [Watt/(m^2 Kelvin)]

K_s = coefficient of heat transfer by radiation between outside surface of lining and inside surface of shell for chimneys with ventilated air spaces [Watt/(m^2 Kelvin)]

k = ratio of wind speed $\bar{V}_*$ to critical wind speed Vcr

k_1 = probability factor (risk coefficient)

$\bar{k}_2$ = terrain, height and structure size factor for hourly mean wind speed

k_3 = topography factor

k_4 = importance factor for cyclone region

L = correlation length coefficient

$\bar{M}_{al}(z)$ = mean along-wind bending moment at height z (N-m)

M_{ac} = across-wind base bending moment at height z (N-m)

$M_{ac}(z)$ = across-wind bending moment at height z (N-m)

$M_{oe}(z)$ = external ring moment due to circumferential wind forces at height z (N-m/m)

$M_{oi}(z)$ = internal ring moment due to circumferential wind forces at height z (N-m/m)

M_u = factored bending moment on the chimney cross-section (N-mm)

$M_{comb}(z)$ = combined design moment at height, z due to across-wind and along-wind loads (N-m)

m_{ave} = average mass in top third of chimney (kg/m)

n = modular ratio of elasticity (E_s/E_c)

P_u = factored axial load on the chimney cross-section (N)

$p(z)$ = design wind pressure at height z, due to 3-s (3 second) gust wind speed, (N/m^2)

$\overline{p}(z)$ = design pressure at height z, due to hourly mean wind speed (N/m^2)

r = mean radius of shell (mm)

r_t = twice the turbulence intensity

$r_m(z)$ = mean radius of the shell at z (m)

r_q = ratio of heat transmission through chimney shell to heat transmission through lining for chimneys with ventilated air spaces

S = size reduction factor

S_t = Strouhal number

S_p = spectral parameter

S_s = mode shape factor

s = centre to centre spacing of chimneys (m)

$t(z)$ = thickness of shell at the section under consideration (m)

T = sample time (s)

T_x = temperature drop across concrete shell (°C)

t = thickness of shell (mm)

t_o = thickness of the shell at bottom (m)

t_H = thickness of the shell at top (m)

$\overline{V}_*$ = hourly mean wind speed at $\frac{5}{6}H$ varying over a range of 0.5 $\overline{V}(z_{ref})$ and 1.3 $\overline{V}(z_{ref})$

V_b = basic wind speed [*see* IS 875 (Part 3)] (m/s)

V_{cr} = critical wind speed for across-wind loads corresponding to fundamental mode (m/s)

$\overline{V}(H)$ = design hourly mean speed at top of chimney (m/s)

$\overline{V}(z)$ = design hourly mean wind speed at any height z (m/s)

$\overline{V}(z_{ref})$ = design hourly mean wind speed at z_{ref} (m/s)

x_u = distance of neutral axis from leeward edge of chimney cross-section (mm)

Y_{max} = maximum lateral deflection (m)

z = height at any section of the chimney above ground level (m)

z_{ref} = reference height = (5/6)H (m)

z_0 = aerodynamic roughness height (m)

α = power law exponent

α_{te} = thermal coefficient of expansion of concrete and of reinforcing steel (/°C)

β_a = aerodynamic damping factor

βs = structural damping as a fraction of critical damping for across-wind load

β = structural damping as a fraction of critical damping for along-wind load

β_1 = one-half central angle subtended by an opening inline with wind direction on the leeward side of chimney cross-section

β_2 = one-half central angle subtended by the two openings symmetric to wind direction

γ_1 = ratio of inside face vertical reinforcement area to outside face vertical reinforcement

γ_1' = ratio of inside face circumferential reinforcement area to outside face circumferential reinforcement

γ_2 = ratio of distance between inner surface of chimney shell and outside face vertical reinforcement to total shell thickness

γ'_2 = ratio of distance between inner surface of chimney shell and outside face circumferential reinforcement to total shell thickness

γ_c = Partial safety factor for concrete

γ_f = Partial safety factor for loads

γ_m = Partial safety factor for material strength

γ_s = Partial safety factor for steel

ε = strain in the chimney cross-section

ε_{cu} = maximum compressive strain in concrete

ε_{su} = maximum strain in steel

δ_s = logarithmic decrement of structural damping

= $2\pi\beta$

ρ = ratio of area of outside face vertical reinforcement to total area of concrete shell

ρ' = ratio of area of outside face circumferential reinforcement to total area of concrete shell

ρ_a = mass density of air

ρ_{ck} = mass density of concrete

θ = one-half central angle subtended by the center lines of two openings symmetric to wind direction

ν = effective cycling rate

In this standard, the SI System of units are used. For example,

a) m (meter) and mm (millimetre) for dimensions.
b) MN (Mega Newton), kN (kilo Newton), and N (Newton) for forces.
c) kg for mass.
d) s (second) for time.
e) GPa (Giga Pascal), N/m^2 (Pascal) and N/mm^2 (Mega Pascal) for stress and pressure.
f) Hz (Hertz) for frequency

4 MATERIALS

4.1 General

All provisions for RCC including their materials shall conform to IS 456 except stated otherwise in this standard.

4.2 Concrete

Concrete quality, the size of aggregates mixing and placing, workmanship, reinforcement details, and durability requirements shall conform to relevant specifications of IS 456, except stated otherwise in this standard.

The grade of concrete shall not be less than M25 for all components of chimney including foundations.

5 LOADS

5.1 Dead Loads

Dead loads shall include the weight of chimney shell, liners, liner supports, other accessories and load of ash and soot as applicable. Unit weight of the materials shall be taken in accordance with IS 875 (Part 1).

5.2 Imposed Loads

Imposed loads shall be taken in accordance with IS 875 (Part 2). The imposed loads on internal platform and hood of multi-flue chimneys shall include appropriate loads during construction.

5.3 Earthquake Loads

Earthquake loads on chimneys shall be computed in accordance with IS 1893 (Part 4) with a response reduction factor R equal to 2 and with an importance factor I equal to 1.75.

5.4 Temperature Effects

Loads due to temperature effects depend on the individual requirements of chimneys and they should be considered accordingly.

5.5 Wind Loads

5.5.1 *General*

Tall RC chimneys of circular cross-section are wind-sensitive structures and they shall be designed to resist both the along-wind and across-wind effects. In addition, the hollow circular cross-section shall be designed to resist the loads caused by the circumferential pressure distribution. For the computation of along-wind loads, the effects of dynamic fluctuations are taken into account as static equivalent loads through the concept of gust response factor, following Davenport's method. For the estimation of across-wind loads the widely used method developed by Vickery and his group, is recommended in this standard.

5.5.2 *Basic Wind Speed*, V_b

The value of basic wind speed, V_b, as recommended in IS 875 (Part 3), shall be considered for design. This corresponds to 3 s averaged wind speed at 10 m height above the ground level, in an open terrain country, having an annual exceedance probability of 0.02.

5.5.3 *Design Hourly Mean Wind Speed,* $\bar{V}(z)$

In this standard for the purpose of computing along-wind loads at various levels along the height of a chimney, the hourly mean wind speed shall be taken as the reference wind speed and at a given height, z, the design wind speed, $\bar{V}(z)$, in m/s can be computed by multiplying V_b, with modification factors, k_1, $\bar{k}_2$, k_3 and k_4, and is given by:

$$\bar{V}(z) = V_b k_1 \bar{k}_2 k_3 k_4$$

where k_1 and k_3 can be obtained from IS 875 (Part 3), and

k_4 shall be taken as 1.15 as recommended in IS 875 (Part 3) for industrial structures.

The value of $\bar{k}_2$ shall be obtained using the following empirical expression for $z > 10$ m,

$$\bar{k}_2 = 0.142\,3\left[\ln\left(\frac{z}{z_0}\right)\right](z_0)^{0.070\,6}$$

where z_0 is the aerodynamic roughness height which shall be taken as 0.02 m for all terrain categories.

NOTE — The value of k_1 to be considered for the unlined chimney case should be same as for the lined chimney case.

5.5.4 *Design Wind Pressure Due to Hourly Mean Wind Speed,* $\bar{p}(z)$

The design wind pressure due to hourly mean wind speed, $\bar{p}(z)$, in N/m^2, corresponding to $\bar{V}(z)$ shall be computed as follows:

$$\bar{p}(z) = \frac{1}{2}\rho_a\left[\bar{V}(z)\right]^2$$

where

ρ_a = mass density of air, taken equal to 1.2 kg/m^3.

5.5.5 *Along-Wind Loads*

The along-wind response of a chimney shall be computed using the Gust factor approach. In general, the chimney shall be discretised into a number of segments along its height with each segment not exceeding 10 m length. The load at any section shall be calculated by suitably averaging the loads above and below it. The moments are calculated from the sectional forces treating the chimney as a free standing structure.

The along-wind load, $F(z)$ per unit height at any level, z on a chimney is equal to the sum of the mean along-wind load, $\bar{F}(z)$ and the fluctuating component of along-wind load, $F'(z)$ and shall be calculated as given below:

$$F(z) = \bar{F}(z) + F'(z)$$

Here, the mean along-wind load, $\bar{F}(z)$ shall be computed as:

$$\bar{F}(z) = \bar{C}_D\, d(z)\bar{p}(z)$$

where

$\bar{C}_D$ = mean drag coefficient taken as 0.8, and

$d(z)$ = outer diameter of chimney at height z.

The fluctuating component of along-wind, $F'(z)$ in N/m, at height z shall be computed as:

$$F'(z) = 3\frac{(G-1)}{H^2}\left(\frac{z}{H}\right)\int_0^H \bar{F}(z)\, z\, dz$$

where

G = gust response factor, (as per **5.5.6**); and

H = total height of the chimney above ground level, in m.

5.5.6 *Gust Response Factor*

The Gust response factor is computed as:

$$G = 1 + g_f r_t \sqrt{B + \left(\frac{SE}{\beta}\right)}$$

where

g_f = peak factor, defined as the ratio of expected peak value to root mean square value of the fluctuating load, given by:

$$g_f = \sqrt{2\ln(\nu T)} + \frac{0.577}{\sqrt{2\ln(\nu T)}}$$

where

$$\nu T = \frac{3\,600\, f_1}{\left(1 + \frac{B\beta}{SE}\right)^{1/2}}$$

ν = effective cycling rate

T = sample period taken as 3 600 s

r_t = twice the turbulence intensity at the top of the chimney, given by :

$$r_t = 0.622 - 0.178 \log_{10} H$$

B = background factor indicating the slowly varying component of wind load fluctuations, given by:

$$B = \left\{1 + \left(\frac{H}{265}\right)^{0.63}\right\}^{-0.88}$$

E is a measure of available energy in the wind at the natural frequency, given by:

$$E = \frac{\left\{123\left(\frac{f_1}{\bar{V}(10)}\right)H^{0.21}\right\}}{\left\{1 + \left(330\frac{f_1}{\bar{V}(10)}\right)^2 H^{0.42}\right\}^{0.83}}$$

S = size reduction factor, given by:

$$S = \left\{1 + 5.78\left(\frac{f_1}{\bar{V}(10)}\right)^{1.14} H^{0.98}\right\}^{-0.88}$$

$\bar{V}(10)$ = mean hourly wind speed at 10 m height above ground level (m/s),

b = structural damping as a fraction of critical damping to be taken as 0.016 for along-wind loads, and

f_1 = natural frequency of unlined chimney in the first mode of vibration, in Hz, as per **5.5.8**.

5.5.7 *Across-Wind Loads*

Across-wind loads due to vortex shedding in the first and second modes shall be considered in the design of all chimney shells when the critical wind speed V_{cr} is between $0.5\,\bar{V}(z_{ref})$ and $1.3\,\bar{V}(z_{ref})$. Across-wind loads need not be considered outside this range.

Across-wind loads shall be calculated as given below, which defines the across-wind base bending moment, M_{ac}

$$M_{ac} = \left[g_{ac} S_s C_L \frac{\rho_a V_{cr}^2}{2} d_e H^2\right] \times \left[\frac{\pi}{4(\beta_s + \beta_a)}\right]^{0.5} S_P \left\{\frac{2L}{\left(\left(\frac{H}{d_e}\right) + C_E\right)}\right\}^{0.5}$$

where

S_s = mode shape factor taken as 0.57 for the 1st mode and 0.18 for the 2nd mode.

C_E = end effect factor taken as 3.

g_{ac} = peak factor for across-wind load taken as 4.0.

d_e = effective diameter taken as average outer diameter over top one-third height of chimney (m).

C_L = RMS lift coefficient and is given by :

$$C_L = C_{Lo}\, F_{1B}$$

where

C_{Lo} = RMS lift coefficient modified for local turbulence and is given by:

$$C_{Lo} = -0.243 + 5.648\, I_{ref} - 18.182\left[I_{ref}\right]^2$$

where

$$I_{ref} = \frac{1.0}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

z_{ref} = reference height, given by :

z_{ref} = $(5/6)H$

$$F_{1B} = -0.089 + 0.337\ \ln\left(\frac{H}{d_e}\right)$$

F_{1B} shall be between 0.2 and 1.0.

V_{cr} = $\frac{f_1 d_e}{S_t}$ for the first mode, and

= $5\, f_2\, d_e$ for the second mode.

where

f_1 and f_2 are the natural frequencies of unlined chimney in the first and second modes of vibration, respectively in Hz as per **5.5.8**.

$S_t = 0.25F_{1A}$

where

$$F_{1A} = 0.333 + 0.206\ \ln\left(\frac{H}{d_e}\right)$$

F_{1A} shall be between 0.6 and 1.0.

$$\beta_s = 0.01 + \frac{0.10\left[\bar{V}_* - \bar{V}(z_{ref})\right]}{\bar{V}(z_{ref})}$$

β_s shall be between 0.01 and 0.04.

$\bar{V}_*$ is to be varied between $0.8V_{cr}$ and $1.2V_{cr}$ (at least 10 intervals shall be considered). The maximum value of $\bar{V}_*$ shall be limited to $1.3\,\bar{V}(z_{ref})$.

$$\beta_a = \frac{K_a \rho_a d_e^{\,2}}{m_{ave}}$$

where

m_{ave} = average mass in top one third of chimney per unit height (kg/m)

K_a = $K_{ao}\, F_{1B}$

where

$$K_{ao} = \frac{-1.0}{\left(1 + 5I_{ref}\right)\left[1 + \frac{|k-1|}{I_{ref} + 0.10}\right]}$$

where

$$k = \frac{\bar{V}_*}{V_{cr}}$$

$$S_p = \frac{k^{1.5}}{\sqrt{B_w}\left(\pi^{0.25}\right)}\exp\left[-\frac{1}{2}\left(\frac{1-k^{-1}}{B_w}\right)^2\right]$$

where

B_w = bandwidth parameter, given by :

B_w = $0.10 + 2\, I_{ref}$

L = correlation length coefficient taken as 1.2.

The maximum value of M_{ac} determined in the region of $0.8V_{cr}$ and $1.2V_{cr}$ shall be taken as the design across-wind base bending moment. When $\bar{V}_* \geq \bar{V}(z_{ref})$, M_{ac} shall be multiplied by

$$\left\{1.0 - 0.95\left[\frac{\bar{V}_* - \bar{V}(z_{ref})}{\bar{V}(z_{ref})}\right]\right\}$$

Using M_{ac}, the across-wind load per unit height at any height, $F_{ac}(z)$ in N/m, shall be calculated based on the corresponding mode shape of the chimney as given below:

$$F_{ac}(z) = \frac{M_{ac}\, m(z)\ \varphi_i(z)}{\int_0^H m(z)\varphi_i(z)\ z\ dz}$$

where

$m(z)$= mass per unit height of chimney at level z (kg/m), and

$\phi_1(z)$ = mode shape corresponding to i^th^ mode.

Using $F_{ac}(z)$, the across-wind bending moments at any height, $M_{ac}(z)$, can be obtained.

5.5.8 *Natural Frequencies*

For preliminary design, the natural frequency of unlined chimney in the first mode of vibration, f_1 (in Hz) may be approximated using the following formula:

$$f_1 = 0.2\left(\frac{d_0}{H^2}\right)\sqrt{\frac{E_{ck}}{\rho_{ck}}}\left(\frac{t_0}{t_H}\right)^{0.3}$$

where

t_0 = thickness of the shell at bottom, in m ;

t_H = thickness of the shell at top, in m;

d_0 = centerline diameter of the shell at bottom in m ;

ρ_{ck} = mass density of concrete, kg/m^3 ; and

E_{ck} = dynamic modulus of elasticity of concrete, in N/m^2.

The following values of the dynamic modulus of elasticity of concrete shall be considered for calculating the natural frequencies:

Grade of Concrete	*Dynamic Modulus of Elasticity* (N/m^2)
M25	3.20×10^{10}
M30	3.35×10^{10}
M35	3.50×10^{10}
M40	3.60×10^{10}
M45	3.72×10^{10}
M50	3.82×10^{10}

Similarly, for preliminary design, the natural frequency of the unlined chimney in the second mode of vibration, f_2 (in Hz) shall be determined using the following formula:

$$f_2 = 6 f_1 \left[\frac{d_H\, t_H}{d_0\, t_0}\right]^{0.2}$$

where

d_H = centerline diameter of the shell at top (m)

However, for final design, the natural frequency shall be computed by dynamic analysis and by discretising the chimney into a number of segments along the height with each segment length not exceeding 10 m.

If the lining is supported in any manner by the shell, the effect of lining on the natural frequency shall be investigated.

5.5.9 *Wind-Induced Interference*

When two identical chimneys are in close proximity, the across-wind load shall be increased to account for the potential increase in vortex induced motions. In such cases, the lift coefficient, C_L shall be modified as follows:

a) if $s/d(z_{ref}) > 12.75$, C_L is unchanged

b) if $3 < s/d(z_{ref}) < 12.75$, C_L shall be multiplied by:

$[0.26 - 0.015\ \{s/d(z_{ref})\}] + [2 - (s/\{12d(z_{ref})\})]$

where

s = centre to centre spacing of chimneys, in m.

For chimneys that are not identical and for identical chimneys where $(s/d(z_{ref})) < 3$, the value of C_L shall be determined based on boundary layer wind tunnel tests on models or observations or test reports of similar arrangements.

5.5.10 *Combination of Across-Wind and Along-Wind Loads*

Across-wind loads shall be combined with co-existing along wind loads. The combined bending moment, $M_{comb}(z)$ at any section shall be taken as resultant of across-wind bending moment $M_{ac}(z)$ and the co-existing mean along-wind bending moment, $\bar{M}_{al}(z)$, and is given by:

$$M_{comb}(z) = \left[(M_{ac}(z))^2 + (\bar{M}_{al}(z))^2\right]^{0.5}$$

$\bar{M}_{al}(z)$ = bending moment induced by mean along-wind load, $\bar{F}_{al}(z)$

where $\bar{F}_{al}(z) = \bar{F}(z)\left(\frac{\bar{V}_*}{\bar{V}(z_{ref})}\right)^2$

except that $\bar{F}_{al}(z)$ shall not exceed $\bar{F}(z)$.

5.5.11 *Circumferential Ring Moments Due to Wind*

The circumferential ring moments due to wind are calculated by the formula:

$$M_{oe}(z) \text{ or } M_{oi}(z) = 0.33\, p(z)(\, r_m(z)\,)^2$$

where

$M_{oe}(z)$ and $M_{oi}(z)$ = external and internal ring moments at height z, respectively, in N-m/m;

$p(z)$ = design wind pressure due to 3 second gust wind speed at height z in N/m^2; and

$r_m(z)$ = mean radius of the shell at the section under consideration, in m.

The design wind pressure (p_z) due to 3 second gust wind speed at height z, for the circumferential ring moments, shall be obtained in accordance with IS 875 (Part 3), treating the chimney as Class A structure in Category 2 terrain.

The pressure (p_z) shall be increased by 50 percent for a distance of $1.5d(H)$ not exceeding 15 m from the top.

The hoop force and shear due to ovalling need not be considered.

5.6 *Load Combinations*

For the overall design of chimney shell and foundation, imposed loads need not be considered. However, for design of individual structural elements such as platforms, etc, and for local strengthening of the shell, appropriate imposed (live) loads shall be considered.

Wind and earthquake loads shall not be considered as acting simultaneously. The various load combinations for the design of chimney shell shall include,

a) dead loads
b) dead loads + wind loads + loads due to temperature effects;
c) dead loads + earthquake loads + loads due to temperature effects; and
d) circumferential ring moments due to wind + due to temperature effects.

6 STRUCTURAL DESIGN (LIMIT STATE METHOD)

6.1 Partial Safety Factors

6.1.1 *Partial Safety Factor (γ_f) for Loads*

The values of γ_f, as given in Table 1 shall normally be used, for combinations involving dead load (DL), wind load (WL) or earthquake load (EL) and loads due to temperature effects (TL).

6.1.2 *Partial Safety Factor (γ_m) for Material Strengths*

When assessing the strength of a structure or structural member for the limit state of collapse, the values of partial safety factor, γ_m, shall be taken as 1.5 for concrete and 1.15 for steel as per IS 456.

6.2 Limit State of Collapse

6.2.1 *Assumptions*

In addition to the assumptions given in **38.1** (a), (d) and (e) of IS 456 for flexure, the following shall be assumed:

a) The maximum compressive strain in concrete in axial compression shall be taken as 0.002. Even in the presence of bending, the strain gradient across the thickness at the extreme compression location is marginal, as the diameter of the chimney is very large in comparison with the thickness of the shell. Hence, the maximum compressive strain at the centre of the shell thickness shall be limited to 0.002 under both axial and flexural compression.
b) The design stress-strain curve for concrete in compression shall be as given in IS 456 with the maximum strain limited to 0.002. The compressive stress is assumed to increase parabolically from zero at zero strain to a peak value of $0.67f_{ck}/\gamma_m$ at a strain of 0.002.
c) For stress-strain relationship of steel, the modulus of elasticity of steel (E_s) is taken as 200 GPa for all types of reinforcing steel (*see* **4.6.2** of IS 456). The stress-strain relationship for steel in tension and compression is assumed to be the same. For high strength deformed (HSD) bars, the stress-strain relationship given as per **38** of IS 456 shall be used. The maximum strain in steel in tension shall be limited to 0.05.
d) As lateral loading induced by wind or earthquake is of very short duration, the strength of concrete ($0.67f_{ck}/\gamma_m$) in flexural compression due to such action may be

Table 1 Values of Partial Safety Factor γ_f for Loads

(*Clause* 6.1.1)

Sl No.	Load Combination	Limit State of Collapse			
		DL	WL	EL	TL
(1)	(2)`	(3)	(4)	(5)	(6)
i)	DL	1.4	—	—	—
ii)	DL + WL + TL	0.9	1.6 (*see* Note)	—	1.2
		1.2	1.6 (*see* Note)	—	1.2
iii)	DL + EL + TL	0.9	—	1.4	1.2
		1.2	—	1.4	1.2
iv)	WL + TL (for circumferential ring moments)	—	1.4	—	1.2

NOTE — The factor 1.6 shall be used for the along-wind loads of **5.5.5**. For the across-wind loading of **5.5.7** combined with the along-wind loading of **5.5.10**, a factor of 1.4 shall be used.

enhanced by a factor C_{sf}. The factor C_{sf} may be defined as the short-term loading factor, having a value between 1.12 for pure bending case and 1.0 for pure compression case (*see* Annex B).

6.2.2 *Design for Combined Axial Load and Uni-Axial Bending*

A section subjected to axial force and uni-axial bending shall be designed on the basis of **6.2.1** under factored loads, satisfying equilibrium of forces, strain compatibility and the design stress-strain curves for concrete and steel. This is likely to involve lengthy calculation using iterative procedures. In order to overcome these difficulties, interaction diagrams may be used. Typical interaction diagrams are presented in Annex B for convenient use by the designer, for cases, a) without opening, b) with one opening, c) with two openings and d) with three openings.

Increase in bending moment due to *P*-delta effects shall be appropriately accounted for.

6.2.3 *Design for Combined Axial Load, Uni-Axial Bending and Temperature Effects*

The generated interaction diagrams as mentioned in **6.2.2** can be used for the design of a section subjected to combined axial load, uni-axial bending and temperature effects except that modified f_y and f_{ck} as given below shall be used.

Replace f_{ck} with

$$f'_{ck} = f_{ck} - \left(\frac{1.2\gamma_m}{0.8}\right) f'_{CTV}$$

Replace f_y with

$$f'_y = f_y - \left(\frac{1.2\gamma_m}{1+\gamma_1}\right) \left(f_{STV} - \gamma_1 f'_{STV}\right)$$

where $f'_{CTV}, \gamma_1, f_{STV}$ and f'_{STV} are defined in **6.2.6**.

NOTE — The evaluated *p* needs to be multilied by (f_y/f'_y)

6.2.4 *Design for Circumferential Ring Moments Due to Wind*

The horizontal strip at any level of the chimney shell shall be designed as a horizontal beam resisting the circumferential ring moments as provided in **5.5.11** along with the γ_f values given in Table 1.

6.2.5 *Design for Combined Circumferential Ring Moments Due to Wind and Temperature Effects*

The chimney shell shall be designed as mentioned in **6.2.4** for combined circumferential ring moments due to wind and temperature effects except that modified f_y and f_{ck} as given below shall be used.

Replace f_{ck} with

$$f'_{ck} = f_{ck} - \left(\frac{1.2\gamma_m}{0.8}\right) f'_{CTC}$$

Replace f_y with $f'_y = f_y - (1.2\gamma_m)\ f_{STC}$

where f'_{CTC} and f_{STC} are defined in **6.2.6**.

6.2.6 *Calculations for Stresses Due to Temperature Effects*

The maximum vertical stress due to temperature in concrete and steel, f'_{CTV} and f'_{STV}, in N/mm^2, occurring at the inside of the chimney shell shall be computed as given below:

$$f'_{CTV} = \alpha_{te}\ c\ T_x\ E_c$$

$$f'_{STV} = \alpha_{te}\ (c - 1 + \gamma_2)\ T_x\ E_s$$

The maximum stress in the vertical steel, f'_{CTV}, in N/mm^2, occurring at the outside face of the chimney shell due to temperature shall be computed as given below

$$f_{STV} = \alpha_{te}\ (\gamma_2 - c)\ T_x\ E_s$$

The maximum circumferential stress due to temperature in concrete, f'_{CTC}, in N/mm^2, occurring at the inside of the chimney shell shall be computed as given below:

$$f'_{CTC} = \alpha_{te}\ c'\ T_x\ E_c$$

The maximum stress in the circumferential steel, f_{STC}, in N/mm^2, occurring at the outside face of the chimney shell due to temperature shall be computed as

$$f_{STC} = \alpha_{te}\ (\gamma_2' - c')\ T_x\ E_s$$

where

α_{te} = thermal coefficient of expansion of concrete and of reinforcing steel and is taken as 0.000 011 7 /°C

$c = -\rho n(\gamma_1 + 1) + \sqrt{[\rho n(\gamma_1 + 1)]^2 + 2\rho n[\gamma_2 + \gamma_1(1-\gamma_2)]}$

$c' = -\rho' n(\gamma_1' + 1) + \sqrt{[\rho' n(\gamma_1' + 1)]^2 + 2\rho' n[\gamma_2' + \gamma_1'(1-\gamma_2')]}$

T_x = temperature drop across concrete shell (°C)

ρ = ratio of area of outside face vertical reinforcement to total area of concrete shell.

ρ' = ratio of area of outside face circumferential reinforcement to total area of concrete shell.

γ_1 = ratio of inside face vertical reinforcement area to outside face vertical reinforcement.

γ_2 = ratio of distance between inner surface of chimney shell and outside face vertical reinforcement to total shell thickness.

γ_1' = ratio of inside face circumferential reinforcement area to outside face circumferential reinforcement.

γ_2' = ratio of distance between inner surface of chimney shell and outside face circumferential reinforcement to total shell thickness.

n = modular ratio of elasticity (E_s / E_c).

The temperature drop across the concrete shell, T_x, shall be computed as given below or by a complete heat-balance study for all operating conditions:

a) For unlined chimneys

$$T_x = \frac{t d_{ci}}{C_c d_c}\left(\frac{T_i - T_o}{\dfrac{1}{K_i} + \dfrac{t d_{ci}}{C_c d_c} + \dfrac{d_{ci}}{K_o d_{co}}}\right)$$

b) For lined chimneys with insulation completely filling the space between the lining and shell

$$T_x = \frac{t d_{bi}}{C_c d_c}\left(\frac{T_i - T_o}{\dfrac{1}{K_i} + \dfrac{t_b d_{bi}}{C_b d_b} + \dfrac{t_s d_{bi}}{C_s d_s} + \dfrac{t d_{bi}}{C_c d_c} + \dfrac{d_{bi}}{K_o d_{co}}}\right)$$

c) For lined chimneys with unventilated air space between the lining and shell

$$T_x = \frac{t d_{bi}}{C_c d_c}\left(\frac{T_i - T_o}{\dfrac{1}{K_i} + \dfrac{t_b d_{bi}}{C_b d_b} + \dfrac{d_{bi}}{K_r d_b} + \dfrac{t d_{bi}}{C_c d_c} + \dfrac{d_{bi}}{K_o d_{co}}}\right)$$

d) For lined chimneys with ventilated air space between the lining and shell

$$T_x = \frac{t d_{bi}}{C_c d_c}\left(\frac{T_i - T_o}{\dfrac{1}{r_q K_i} + \dfrac{t_b d_{bi}}{r_q C_b d_b} + \dfrac{d_{bi}}{K_s d_s} + \dfrac{t d_{bi}}{C_c d_c} + \dfrac{d_{bi}}{K_o d_{co}}}\right)$$

where

d_b = centerline diameter of uninsulated lining or insulation around liner, in m;

d_{bi} = inside diameter of uninsulated lining or insulation around liner, in m;

d_c = centerline diameter of concrete chimney shell, in m;

d_{ci} = inside diameter of concrete chimney shell, in m;

d_{co} = outside diameter of concrete chimney shell, in m; and

d_s = centerline diameter of space between lining and shell, in m.

Unless complete heat balance studies are made for the particular chimney, it is permissible to use the approximate values given as follows. These constants, when entered into equations for temperature differential through the chimney shell, T_x will give values of accuracy in keeping with the basic design assumptions:

r_q = ratio of heat transmission through chimney shell to heat transmission through lining for chimneys with ventilated air spaces and is taken as 0.5

C_c = coefficient of thermal conductivity of concrete of chimney shell and is taken as 1.73 [Watt / (m K)].

C_s = coefficient of thermal conductivity of insulation filling in space between lining and shell, to be obtained from the manufacturer of the materials used [Watt / (m K)].

C_b = coefficient of thermal conductivity of chimney uninsulated lining or insulation around steel liner, to be obtained from the manufacturer of the materials used [Watt / (m K)].

K_i = coefficient of heat transmission from gas to inner surface of chimney lining when chimney is lined, or to inner surface of chimney shell when chimney is unlined, to be determined from curves as shown in Fig. 1

K_o = coefficient of heat transmission from outside surface of chimney shell to surrounding air and is taken as 68 [Watt / (m^2 Kelvin)].

K_r = coefficient of heat transfer by radiation between outside surface of lining and inside surface of concrete chimney shell and is taken as T_i / 9.75.

K_s = coefficient of heat transfer by radiation between outside surface of lining and inside

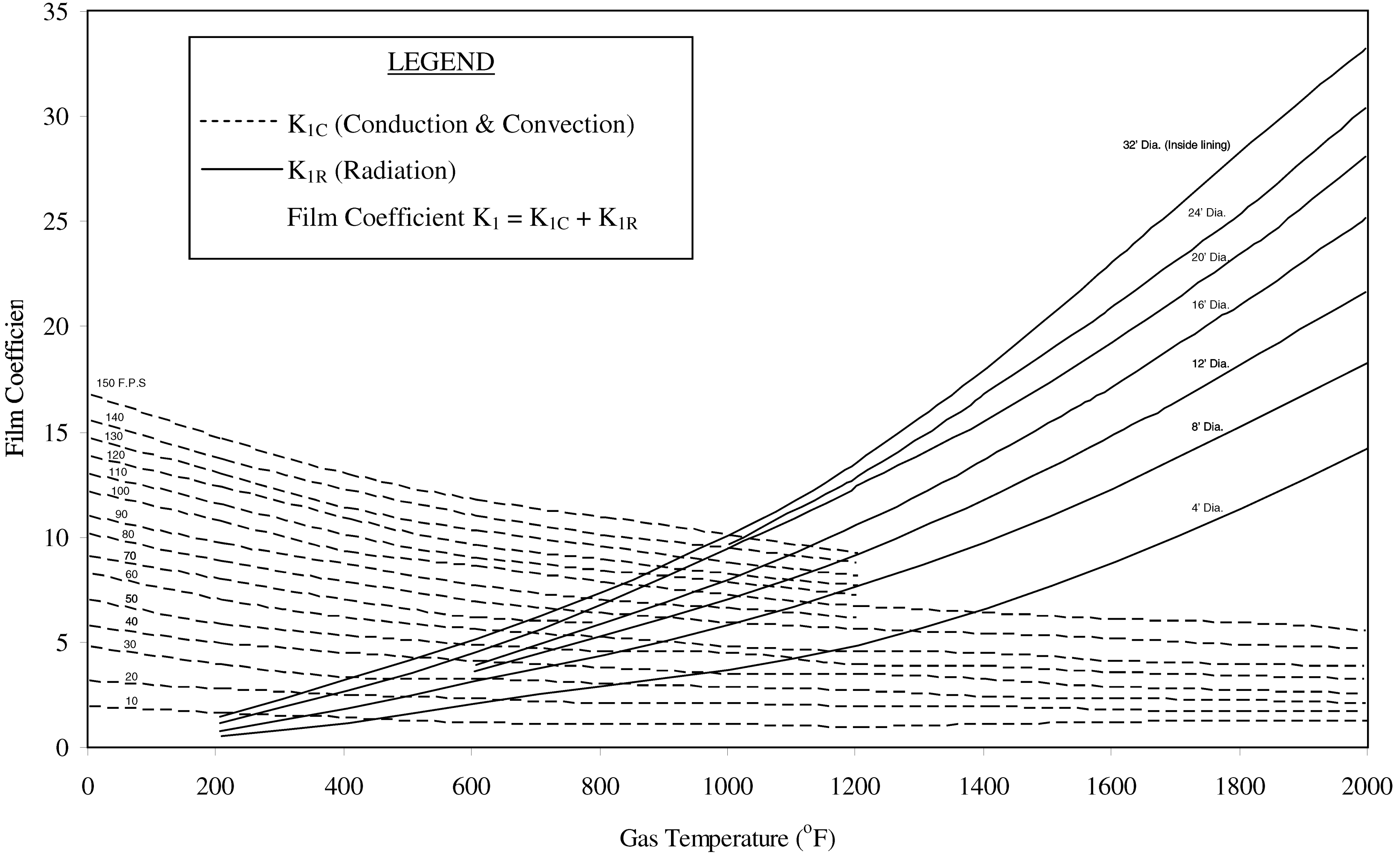


FIG. 1 CURVES FOR DETERMINING K$_1$

surface of shell for chimneys with ventilated air spaces and is taken as T_i / 9.75.

The value of $r_q = 0.5$ shall apply only where the distance between the lining and the chimney shell is not less than 100 mm the entire height of the lining and air inlet and outlet openings are provided at the bottom and top of the chimney shell. The area of the inlet and outlet openings, in square meter, shall numerically equal to two-thirds of the inside diameter in meter of the chimney shell at the top of the lining. Local obstructions in the air space between the lining and the chimney shell shall not restrict the area of the air space at any horizontal section to less than that specified for air inlet or outlet.

6.3 Limit States of Serviceability

6.3.1 *Deflection*

The maximum lateral deflection of the top of a chimney under all service conditions with $\gamma_f = 1.0$ for all loads shall be limited to H/500, where H is the total height of the chimney above the ground level. In the deflection calculation, modulus of elasticity of concrete (E_c) as per IS 456 shall be used.

6.3.2 *Cracking*

The provisions as per **43** of IS 456 shall apply.

6.4 Minimum Requirements

6.4.1 *Thickness of Concrete Shell and R.C. Components*

a) The minimum thickness of concrete shell for any chimney with an internal diameter of 6 m or less shall be 150 mm. When the internal diameter exceeds 6 m, the minimum thickness, in mm, shall be, $\left(150 + \frac{d_{ci} - 6\,000}{120}\right)$, where d_{ci} is the inside diameter of the concrete shell in mm. In any case, the minimum thickness at top for single brick flue chimney shall not be less than 200 mm and that for multi-flue chimney, shall not be less than 400 mm. Where slip form is used for construction of shell, the minimum thickness of shell shall be 200 mm.

b) The shell thickness through openings shall be more than 1/24 times height of the opening. Such thickness shall extend at-least half the opening height on all four sides of the opening. However, no advantage shall be taken for such local thickening in the design of chimney.

c) The minimum thickness of the corbels shall not be less than 125 mm

d) The minimum thickness of hopper shell of concrete shall not be less than 125 mm.

e) The minimum thickness of platform of concrete shall not be less than 125 mm.

6.4.2 *Reinforcement in Shell*

6.4.2.1 *Vertical reinforcement*

a) The minimum vertical reinforcement shall be 0.25 percent, for HYS deformed bars, of the concrete area of the section under consideration. For mild steel bars the minimum reinforcement may be 0.3 percent of the concrete area of the section under consideration.

b) Where stress considerations demand and where the shell thickness exceeds 200 mm, two layers of reinforcement shall be provided, one near each face to make up the minimum reinforcement specified in **6.4.2.1** (a). The reinforcement provided on outer face shall not be less than the reinforcement on inner face.

c) The minimum diameter of bars shall not be less than 12 mm. The maximum centre to centre distance of reinforcement shall not exceed 200 mm or the shell thickness, whichever is less when provided in a single layer. The maximum centre to centre distance of reinforcement shall not exceed 300 mm or the shell thickness which ever is less in each layer and shall be staggered symmetrically when provided in two layers. It shall be preferable to use smaller diameter bars with lesser centre to centre spacing.

d) Laps for reinforcement shall be staggered. Not more than one-third of the bars shall be lapped at any one level.

6.4.2.2 *Circumferential reinforcement*

a) The circumferential reinforcement shall be not less than 0.2 percent, when HYS deformed bars are used, of the concrete area in vertical section under consideration subject to a minimum of 400 mm^2 /m height of the chimney. When mild steel bars are used the minimum percentage shall be 0.3. If the vertical reinforcement is provided in two layers, then the circumferential reinforcement shall also be provided in two layers and the minimum reinforcement specified above shall be divided equally in each layer. The spacing of bars shall not be more than 300 mm or the shell thickness whichever is less. The minimum diameter of circumferential reinforce shall be 10 mm.

b) Circumferential reinforcement shall be placed on the outer side of the vertical reinforcement when provided in one layer. When provided in two layers, circumferential reinforcement shall be placed nearer the faces of the shell.

c) Laps shall be staggered such that centre to centre distance of the splices is not less than 1.3 times lap length in any three adjacent layers.

6.4.3 *Foundations*

6.4.3.1 *General*

Shallow (raft) or deep (piled) foundations may be provided for chimneys as required from geotechnical considerations. Foundations must be designed to transfer the vertical (gravity) and lateral (wind/ earthquake) loads safely to the sub-grade. The foundations must also be sufficiently rigid to prevent excessive deflection of the chimney.

Tall chimneys are more susceptible to differential settlement than ordinary structures firstly because the width of the foundation is small in relation to the height of the structure, and secondly because of the lack of redundancy in the structure.

Uplift shall not be permitted for a raft foundation under the critical load combination of (0.9DL + 1.0WL). For piled foundations, the tension capacity of the piles may be utilised to permit a small amount of uplift.

6.4.3.2 *Layout of foundations*

Foundations for chimneys are usually circular or annular in plan. Polygonal raft/ pile cap with 8 or more sides may also be used. Foundations may be simple solid slabs or cellular, consisting of top and bottom slabs interconnected by vertical diaphragms.

6.4.3.3 *Stability*

The stability of chimney shall be ensured as per **20** of IS 456.

6.4.3.4 *Analysis*

Foundations may be analyzed by using typical elastic analysis procedures. Detailed finite element analyses are desirable for unusual geometries and cellular foundations. Plastic (yield line) analysis may also be carried out, if required.

Simple elastic analysis based on the assumption of rigid foundation and uniform thickness may be used strictly within the following limitations.

a) The foundation is relatively rigid. The foundation may be assumed to be rigid, if the diameter to depth ratio does not exceed 12 and if the overhang of the foundation beyond the shell does not exceed four times the thickness.
b) The foundation consists of a solid raft or pile cap.
c) The raft/ pile cap is uniform in depth or tapered only very slightly (taper not exceeding 1 in 8).

6.4.3.5 *Design*

The structural design of the foundation shall comply with the limit states design requirements for strength and serviceability (cracking) of IS 456.

6.4.4 *General*

a) Hooks in reinforcing bars shall preferably be avoided, where necessary laps may be provided or the reinforcement may be welded or mechanical couplers may be used. Laps and welds shall be staggered.
b) *Cover* – The clear concrete cover over the reinforcement shall not be less than 50 mm.

7 OPENINGS

The one-half opening angle of any opening shall not exceed 22.5°. The cumulative of all opening angles at any cross-section shall not exceed 72°.

The steel bars cut by the openings shall be replaced at the sides of the openings, with equivalent area of steel.

In addition to the reinforcement determined by design, additional reinforcement shall be provided at the sides, top, bottom, and corners of all openings as hereinafter specified. This additional reinforcement shall be placed as close to the opening as proper spacing of bars shall permit. Unless otherwise specified, all additional reinforcement shall extend past the opening to a minimum of the development length.

At each side of the opening, the additional vertical reinforcement shall have an area at least equal to the design steel ratio times one-half the area of the opening. This additional reinforcement shall be placed within a distance not exceeding three times the wall thickness unless otherwise determined by a detailed analysis. If the additional vertical reinforcement is not placed in the same layer as the inside and outside vertical reinforcement, tie bars shall be provided to brace the additional vertical reinforcement. *See* Fig. 2 for details.

At both the top and bottom of each opening, additional reinforcement shall be placed having an area at least equal to one-half the established design circumferential reinforcement interrupted by the opening. The area A_s of this additional steel at the top and at the bottom, however, shall be not less than that given below unless otherwise determined by a detailed analysis:

$$A_s = \frac{0.048 f_{ck}\, tl}{f_y}$$

One-half of this extra reinforcement shall extend completely around the circumference of the chimney, and the other half shall extend beyond the opening for a minimum of development length. This reinforcement shall be placed as close to the opening as practicable, but within a height/distance not to exceed three times the thickness‘*t*’.

For openings larger than 600 mm, diagonal reinforcing bars with a total cross-sectional area, in cm^2, of not less than half the shell thickness, in cm, shall be placed at each corner of the opening. Such diagonal bars shall extend past the opening corner on each side up to a distance sufficient to develop the required bond. For openings 600 mm wide or smaller, a minimum of two reinforcing bars of 16 mm diameter shall be placed diagonally at each corner of the opening.

Tie bars shall be provided between inner and outer face reinforcement around the perimeter of all openings where reinforcing steel is interrupted and at the top of chimney shells. Ties shall be a minimum of 10 mm dia. bars, and shall not exceed a spacing of 300 mm. (*see* Fig. 2).

Spacing of ties shall confirm to the requirements of ties as per **26.5.3.2** of IS 456.

8 CONSTRUCTION REQUIREMENTS

8.1 Forms

a) Forms for the chimney shell shall be made of metal, wood, or other suitable materials.

b) Forms shall be sufficiently tight to prevent leakage of mortar.

c) Load shall not be placed on the concrete structure until that portion of the structure has attained sufficient strength to safely support its weight and the loads placed thereon.

d) Forms shall be removed in such manner as to ensure the safety of the structure. Forms shall be permitted to be removed after the concrete has hardened to a sufficient strength to maintain its shape without damage and to safely support all loads on it, including temporary construction loads.

e) Ties between inner and outer chimney shell forms shall not be permitted.

f) Construction joints shall be properly prepared to facilitate bonding. As a minimum requirement, all laitance and loose material shall be removed.

8.2 Reinforcement placement

a) Circumferential reinforcement shall be placed around the exterior of, and secured to, the vertical reinforcement bars. All reinforcing bars shall be tied at intervals of not more than 600 mm. Bars shall be secured against displacement within the tolerances mentioned in IS 456.

b) Vertical reinforcement projecting above the forms for the chimney shell shall be temporarily supported so as to prevent the breaking of the bond with the freshly placed concrete.

8.3 Concrete Placement

All concrete placement shall conform to IS 456, and shall be placed in layers no greater than 400 mm. Vertical construction joints for chimney shells shall not be used. Where used, horizontal construction joints for cast-in-place concrete shall be approximately evenly spaced throughout the height of the chimney shell.

8.4 Concrete Curing

a) Immediately after the forms have been removed, all necessary finishing of concrete shall commence.

b) As soon as finishing has been completed, both faces of concrete shall be cured by coating with a membrane-curing compound or other method approved by the design engineer-in-charge.

8.5 Construction Tolerances

The chimney shell shall be constructed within the tolerance limits set forth herein.

8.5.1 *Vertical Alignment of Center point*

The actual centre point of the shell shall not deviate from its theoretical axis by more than 1/1 000 times the height of the shell, subject to maximum of 100 mm. Locally, the actual centre point of the shell shall not deviate horizontally by more than 25 mm for any 3 m of vertical rise.

8.5.2 *Diameter*

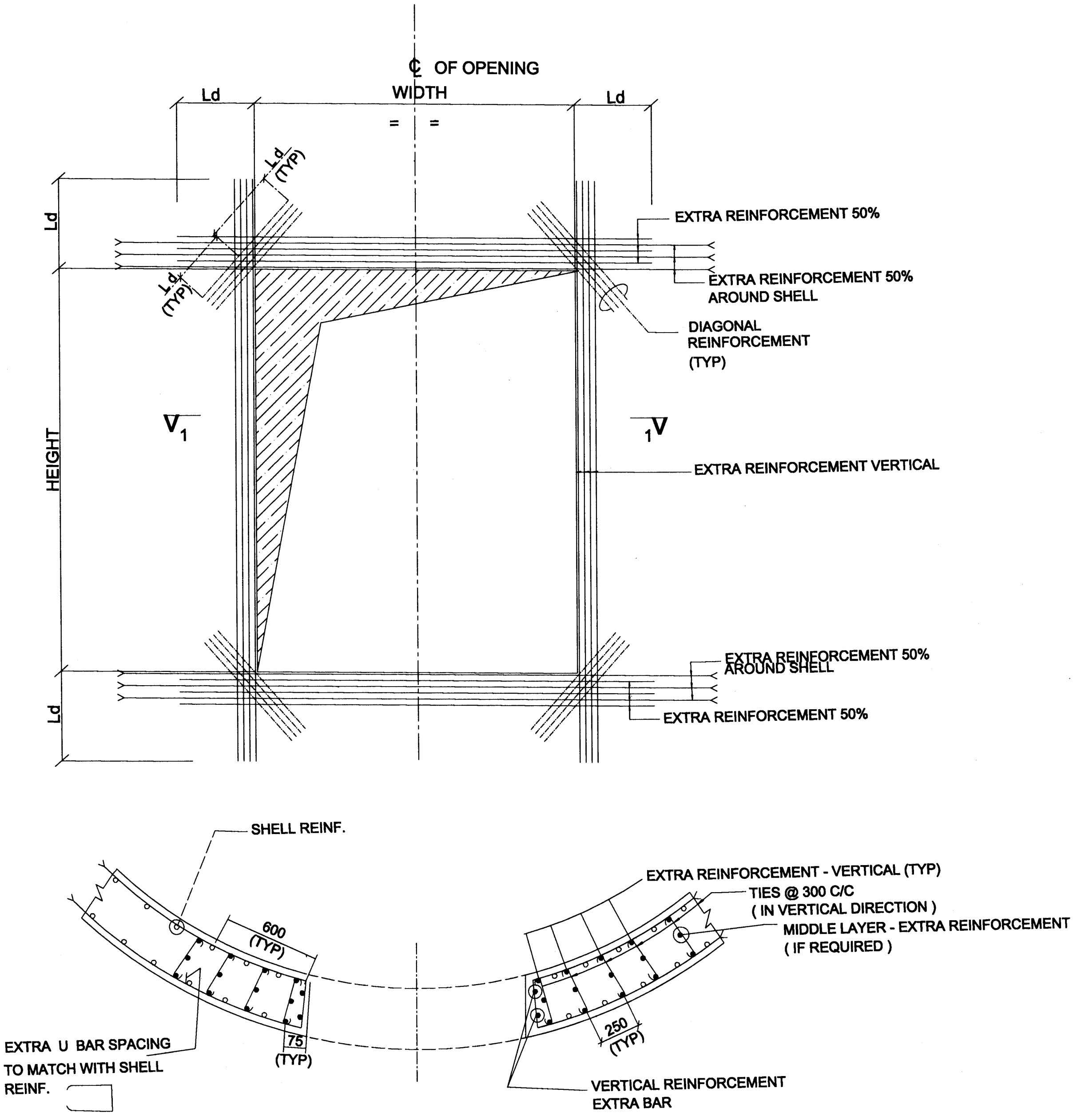
The measured outside shell diameter at any section shall not deviate from the specified diameter by ± (25 mm + 12.5 mm / 3 m of specified diameter), but in no case more than ± 75 mm.

8.5.3 *Wall Thickness*

The measured wall thickness shall not deviate beyond the range of -6 mm to +12 mm for specified wall thickness $\leq$ 250 mm, and shall not deviate beyond the range of -10 mm to +25 mm for specified wall thickness > 250 mm. A single wall thickness measurement is defined as the average of at least four measurements taken at a uniform spacing over a 60° arc. A negative tolerance decreases the overall thickness, and a positive tolerance increases the overall thickness.

8.5.4 *Openings and Embedments*

Tolerances on the size and location of openings and embedments in the shell cannot be uniformly established due to the varying degrees of accuracy required, depending on the nature of their use. Appropriate tolerances for opening and embedment sizes and locations shall be established for each chimney.


℄ OF OPENING
WIDTH
Ld
Ld
=
=
Ld (TYP)
Ld (TYP)
Ld
HEIGHT
Ld
V1
1V
EXTRA REINFORCEMENT 50%
EXTRA REINFORCEMENT 50% AROUND SHELL
DIAGONAL REINFORCEMENT (TYP)
EXTRA REINFORCEMENT VERTICAL
EXTRA REINFORCEMENT 50% AROUND SHELL
EXTRA REINFORCEMENT 50%
SHELL REINF.
600 (TYP)
75 (TYP)
EXTRA U BAR SPACING TO MATCH WITH SHELL REINF.
EXTRA REINFORCEMENT - VERTICAL (TYP)
TIES @ 300 C/C (IN VERTICAL DIRECTION)
MIDDLE LAYER - EXTRA REINFORCEMENT (IF REQUIRED)
250 (TYP)
VERTICAL REINFORCEMENT EXTRA BAR

SECTION 1-1

FIG. 2 EXTRA REINFORCEMENT AROUND OPENING

ANNEX A

(*Clause* 2)

LIST OF REFERRED INDIAN STANDARDS

IS No.	*Title*
456 : 2000	Plain and reinforced concrete — Code of practice (*fourth revision*)
1893	Criteria for earthquake resistant design of structures:
(Part 4) : 2015	Industrial structures including stack like structures (*under print*)
875	Code of practice for design loads (other than earthquake) for buildings and structures
(Part 1) : 1987	Dead loads (*second revision*)
(Part 2) : 1987	Imposed loads (*second revision*)
(Part 3) : 2015	Wind loads (*third revision*)
11089 : 1984	Code of practice for design and construction of ring foundations
15498 : 2004	Guidelines for improving the cyclonic resistance of low rise houses and other buildings/structures

ANNEX B

[*Clauses* 6.2.1 (d) *and* 6.2.2]

B-1 DESIGN STRENGTH OF CIRCULAR CHIMNEY SECTION

The circular section of chimney is idealized as a shaft with mean radius '*r*' with thickness of '*t*' and percentage of steel of '*p*'. The interaction curves / envelops for the chimney cross-section have been generated using the following stress-strain relationships.

The stress-strain relationship for concrete in compression (strength of concrete in tension is assumed to be zero) is taken as:

$$f_c = \frac{0.67 C_{sf} f_{ck}}{\gamma_c}\left\{2\left(\frac{\varepsilon}{\varepsilon_{cu}}\right)-\left(\frac{\varepsilon}{\varepsilon_{cu}}\right)^2\right\} \text{ for } \varepsilon \le \varepsilon_{cu}$$

where

ε_{cu} = 0.002

f_{ck} = characteristic cube strength of concrete (N/mm^2)

γ_c = 1.5

C_{sf} = short-term loading factor
= $[0.95 - 0.1\ (P_u/P_{umax})]/0.85$

P_u = Factored axial load

$$P_{umax} = 2\pi rt\left[\left(\frac{0.67 f_{ck}}{\gamma_c}\right)\left(1-\frac{p}{100}\right)+f_s(\varepsilon_{cu})\left(\frac{p}{100}\right)\right]$$

Here $f_s(\varepsilon_{cu})$ is stress in steel corresponding to strain of ε_{cu}.

The stress-strain relationship for mild steel bars in tension (–ve) / compression (+ve) is taken as

$$f_s = \begin{cases} E_s\ \varepsilon\ \ for\ -\varepsilon_{sy} \le \varepsilon \le \varepsilon_{sy} \\ \dfrac{f_y}{\gamma_s}\ (\varepsilon/|\varepsilon|)\ \ for\ \ \varepsilon_{sy} < |\varepsilon| \le \varepsilon_{su} \end{cases}$$

where

$$\varepsilon_{sy} = \frac{f_y}{\gamma_s E_s}$$

γ_s = 1.15

E_s = 200000 N/mm^2

ε_{su} = 0.07

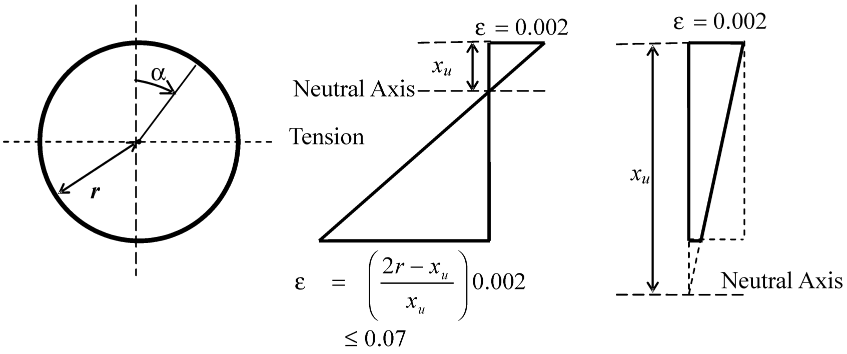
The stress-strain relationship for cold worked steel bars in tension/compression is taken as per Table 2.

Table 2

Stress (f_s)	**Strain (ε)**
Upto $0.8 f_y / \gamma_s$	$0.8 f_y / (\gamma_s E_s)$
$0.85 f_y / \gamma_s$	$[0.85 f_y / (\gamma_s E_s)]$ + 0.000 1
$0.9 f_y / \gamma_s$	$[0.9 f_y / (\gamma_s E_s)]$ + 0.000 3
$0.95 f_y / \gamma_s$	$[0.95 f_y / (\gamma_s E_s)]$ + 0.000 7
$0.975 f_y / \gamma_s$	$[0.975 f_y / (\gamma_s E_s)]$ + 0.00 10
f_y / γ_s	$[f_y / (\gamma_s E_s)]$ + 0.00 20
f_y / γ_s	Up to 0.05

Note — to take into account the tension/compression effect a sign of $(\varepsilon/|\varepsilon|)$ need to be used with f_s

The strain distribution lines for the cases of (i) neutral axis lying within the section and (ii) neutral axis lying outside the section are shown in Fig. 3. In the case of neutral axis lying outside the section, the strain



(a) Neutral axis within section

(b) Neutral axis outside section

FIG 3 STRAIN DISTRIBUTION LINES

distribution line is varied by increasing the strain at minimum compressive side of the section from 0 to 0.002 (with 10 intervals) and by keeping the strain at the maximum compressive side of the section as 0.002 (*see* Fig. 3).

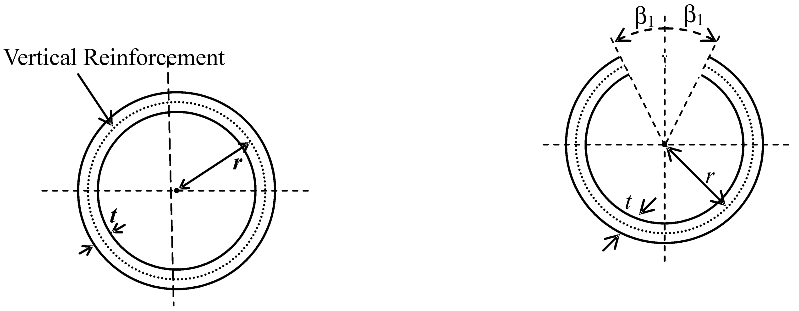
Using the above mentioned stress-strain relationships for concrete and steel, P_u and M_u have been obtained for different locations of the neutral axis (both inside the cross-section and outside cross-section) by integrating the stresses along with area of cross-section (for P_u) and along with lever arm also about the centre of the chimney cross-section (for M_u) as given below:

$$P_u = \int_0^{\pi} f_c \left(1 - \frac{p}{100}\right) 2rt\, d\alpha + \int_0^{\pi} f_s \left(\frac{p}{100}\right) 2rt\, d\alpha$$

$$M_u = \int_0^{\pi} f_c \left(1 - \frac{p}{100}\right) 2rt(r\cos\alpha)\, d\alpha + \int_0^{\pi} f_s \left(\frac{p}{100}\right) 2rt(r\cos\alpha)\, d\alpha$$

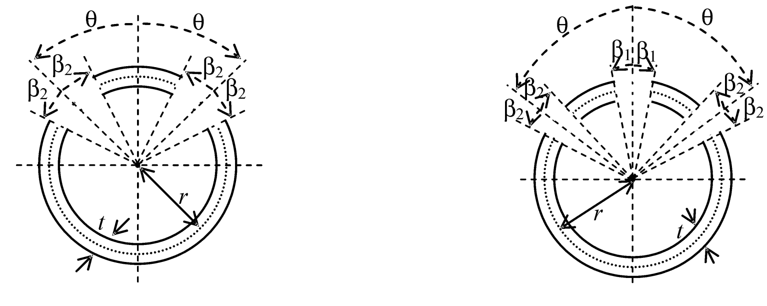
To account for the minimum eccentricity criteria as given in **39.2** of IS 456, the interaction diagrams have been limited to $P_u/(f_{ck}\, r\, t)$ corresponding to the P_u given in **39.3** of IS 456.

Design interaction diagrams for chimney cross-section with no-opening, single-opening, two-openings and three-openings cases have been generated by normalizing P_u as $P_u/(f_{ck} rt)$ and M_u as $M_u/(f_{ck}\, r^2 t)$ with the layouts and notations as shown in Fig. 4. For generating the interaction diagrams, (p/f_{ck}) is varied



(a) Without opening

(b) With one opening



(c) With two openings

(d) With three openings

FIG. 4 CASES OF OPENINGS IN THE CHIMNEY CROSS-SECTION

as 0.00, 0.01, 0.02, 0.3, 0.04, 0.05, 0.06, 0.07, 0.08; β_1 and β_2 are varied as 10°, 20° 30°; θ varied as 60°, 90°, 120° and 150°).

Since the steel bars cut by the openings are replaced at the sides of the openings with equivalent area of steel (*see* **7**), the following approximations are made while generating the interaction diagrams for sections with openings: (a) openings in the tension zone are ignored because the tensile strength of the concrete is also neglected, and (b) openings in the compression zone are ignored for the calculation of forces in the compression reinforcement only.

Typical interaction diagrams generated for f_y = 415 N/mm^2 are shown in Fig. 5 to Fig. 17 and for f_y = 500 N/mm^2 in Fig. 18 to Fig. 30.

The one-half opening angle (β_1, β_2) shall not exceed 22.5°. Where the opening configuration does not match with the given provisions, appropriate methods consistent with the assumptions given in **6.2.1** shall be used.

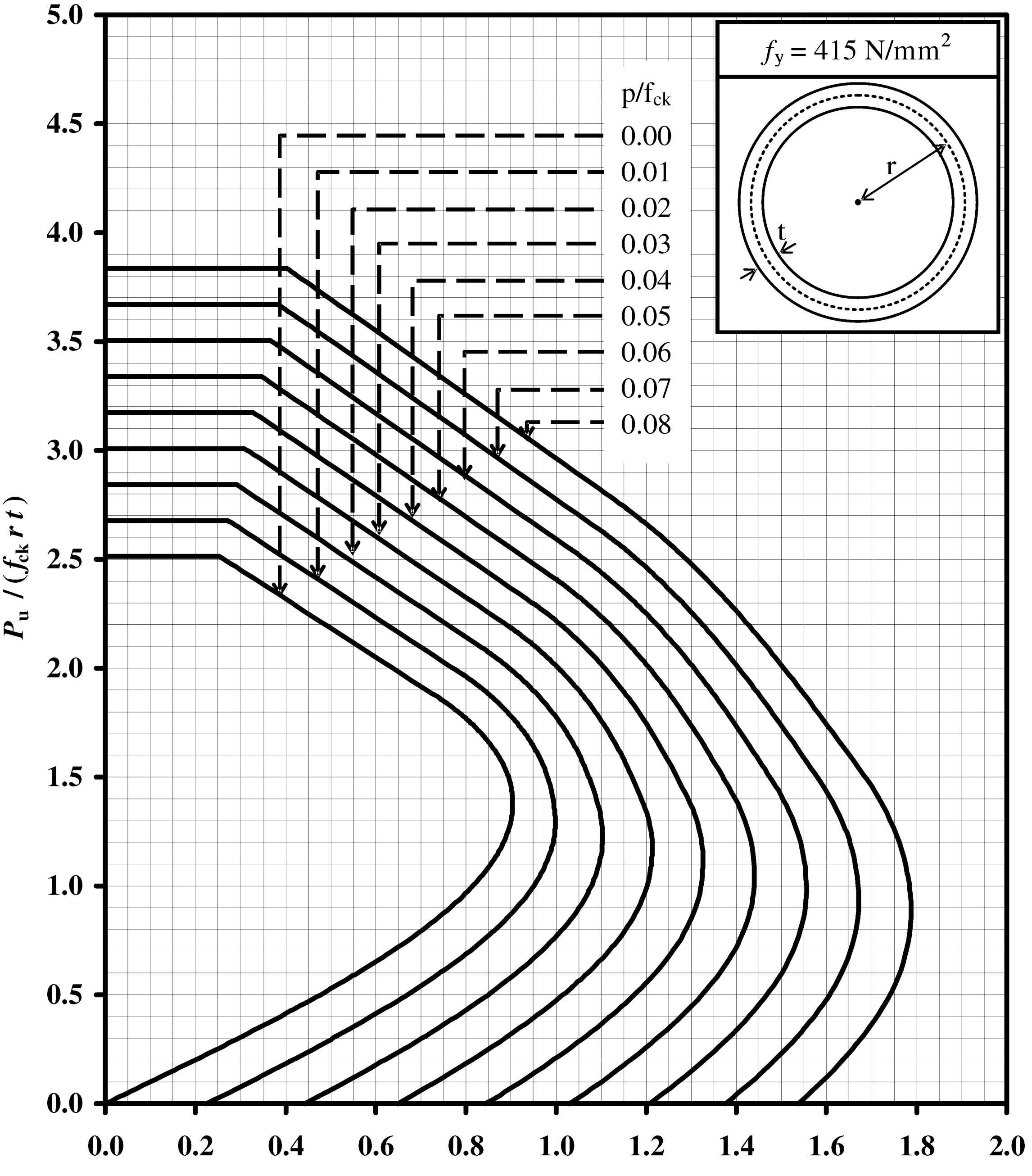


FIG. 5 INTERACTION DIAGRAM FOR SECTION WITHOUT OPENING

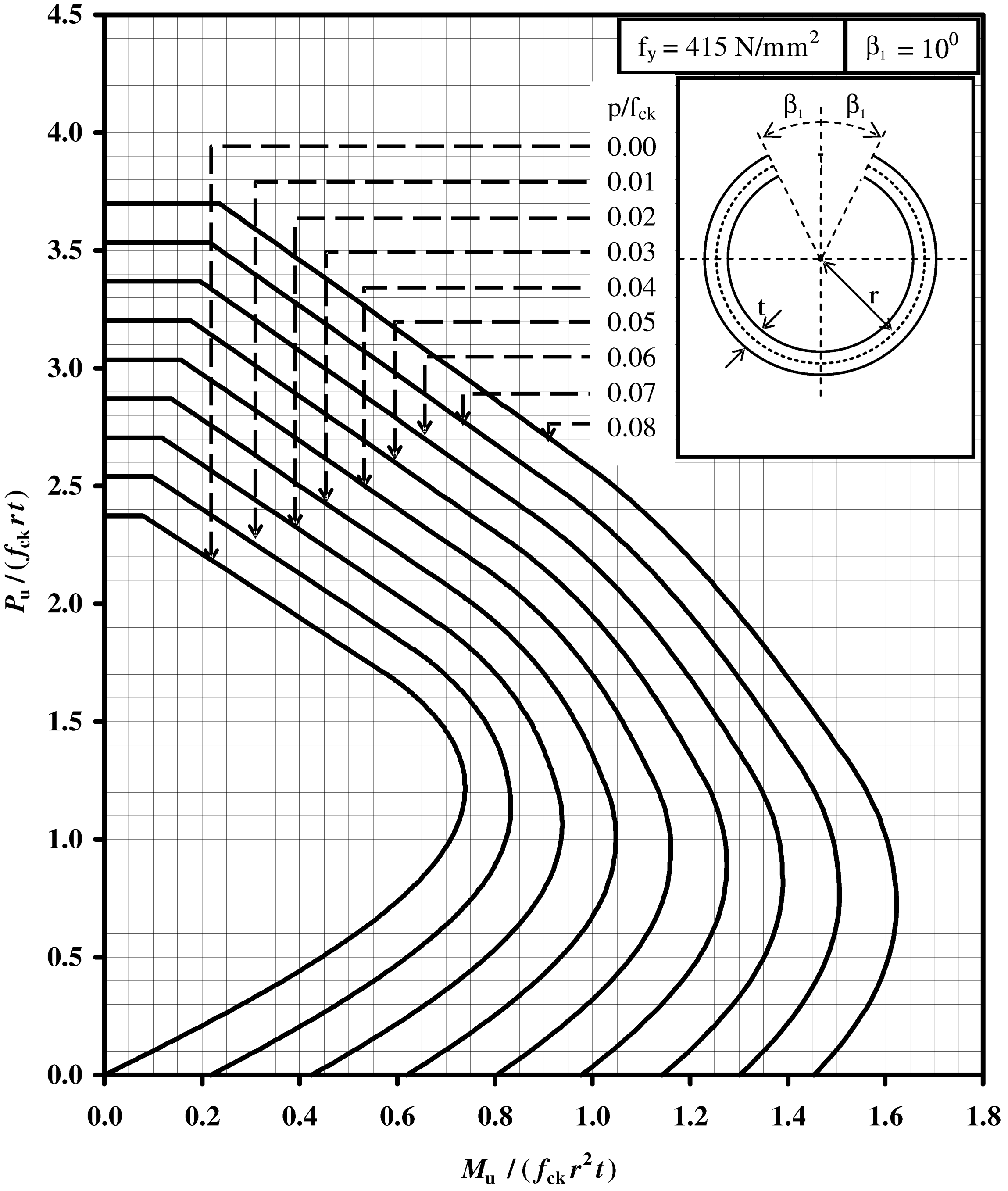


FIG. 6 INTERACTION DIAGRAM FOR SECTION WITH ONE OPENING

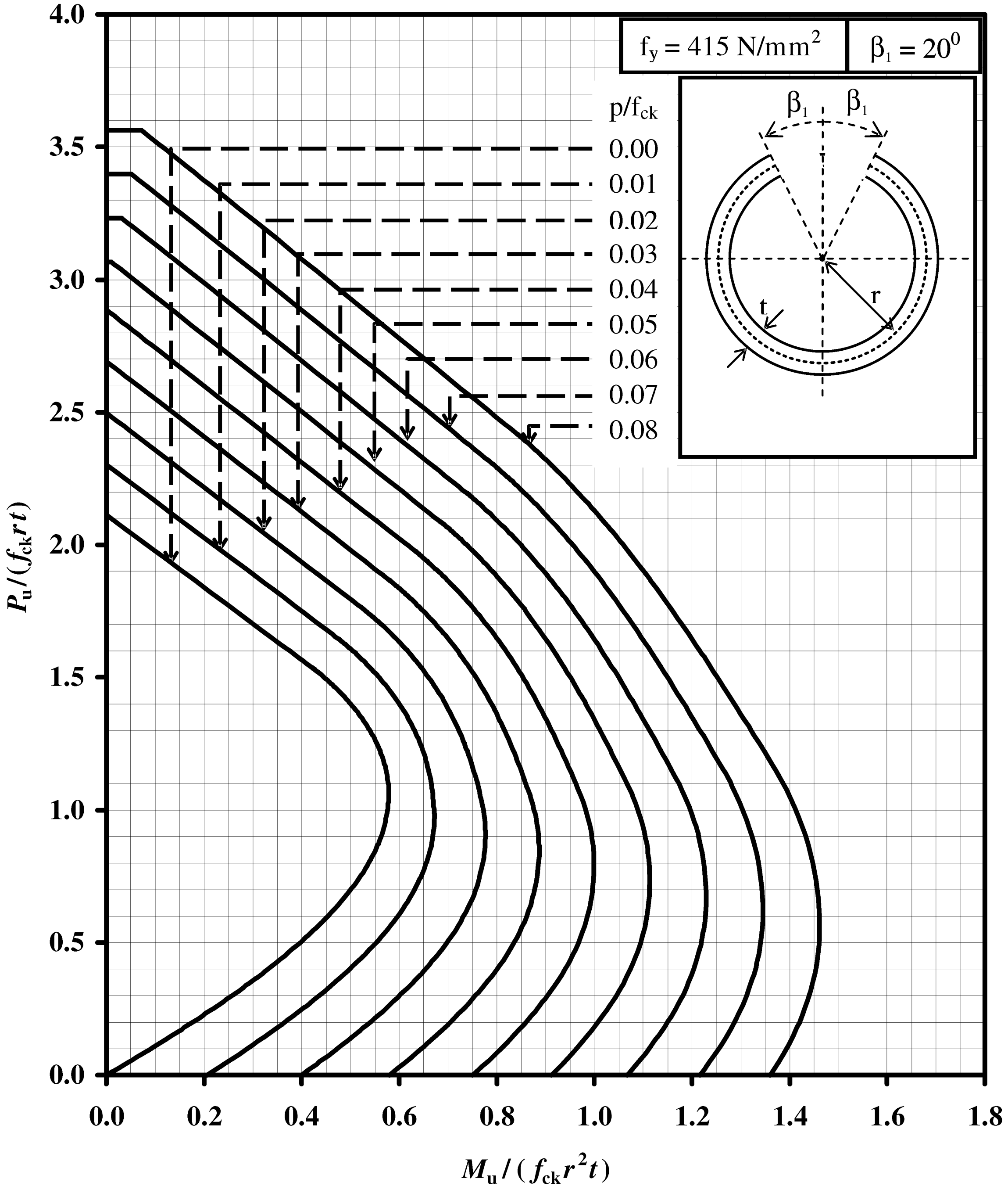


FIG. 7 INTERACTION DIAGRAM FOR SECTION WITH ONE OPENING

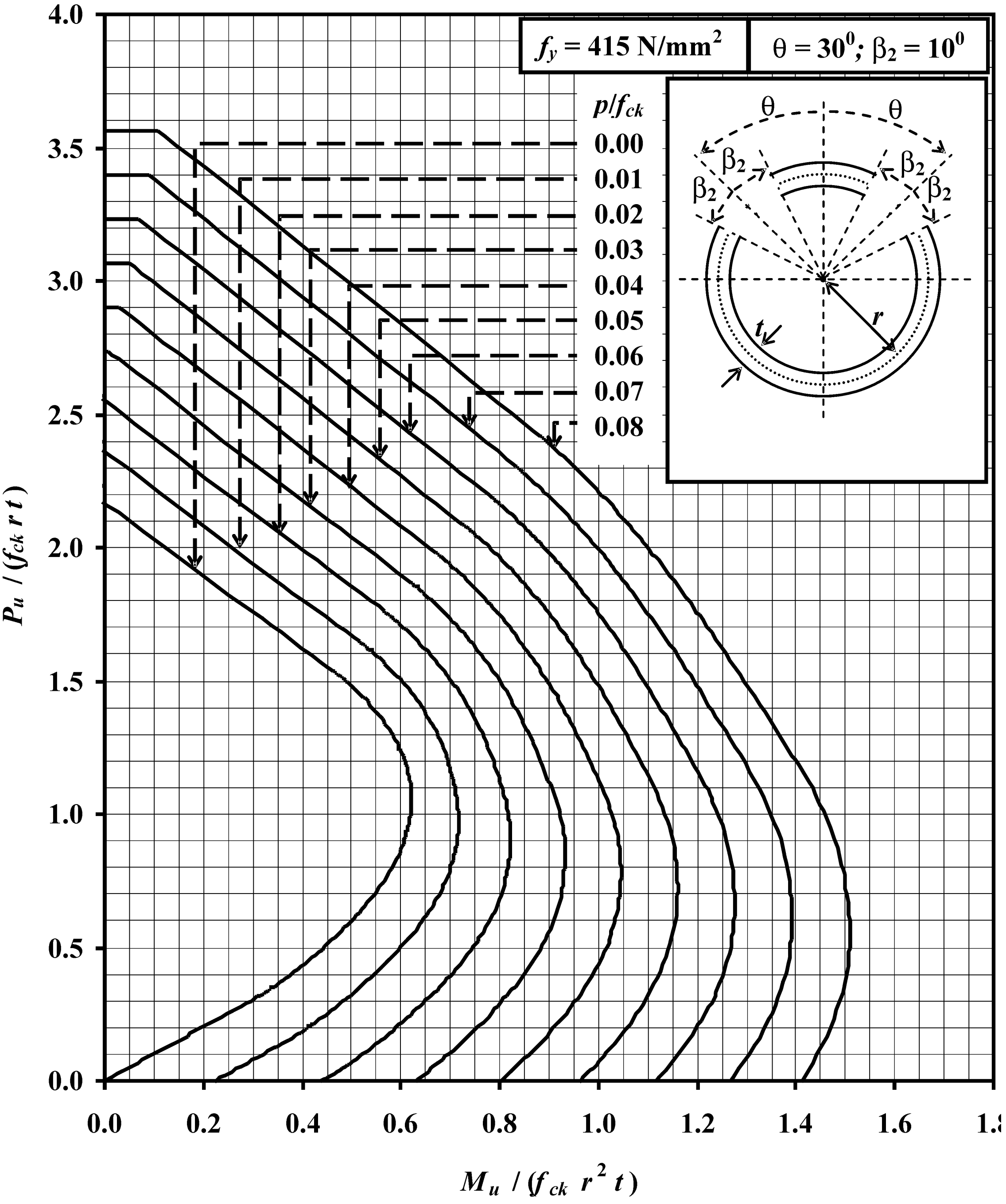


FIG. 8 INTERACTION DIAGRAM FOR SECTION WITH TWO OPENINGS

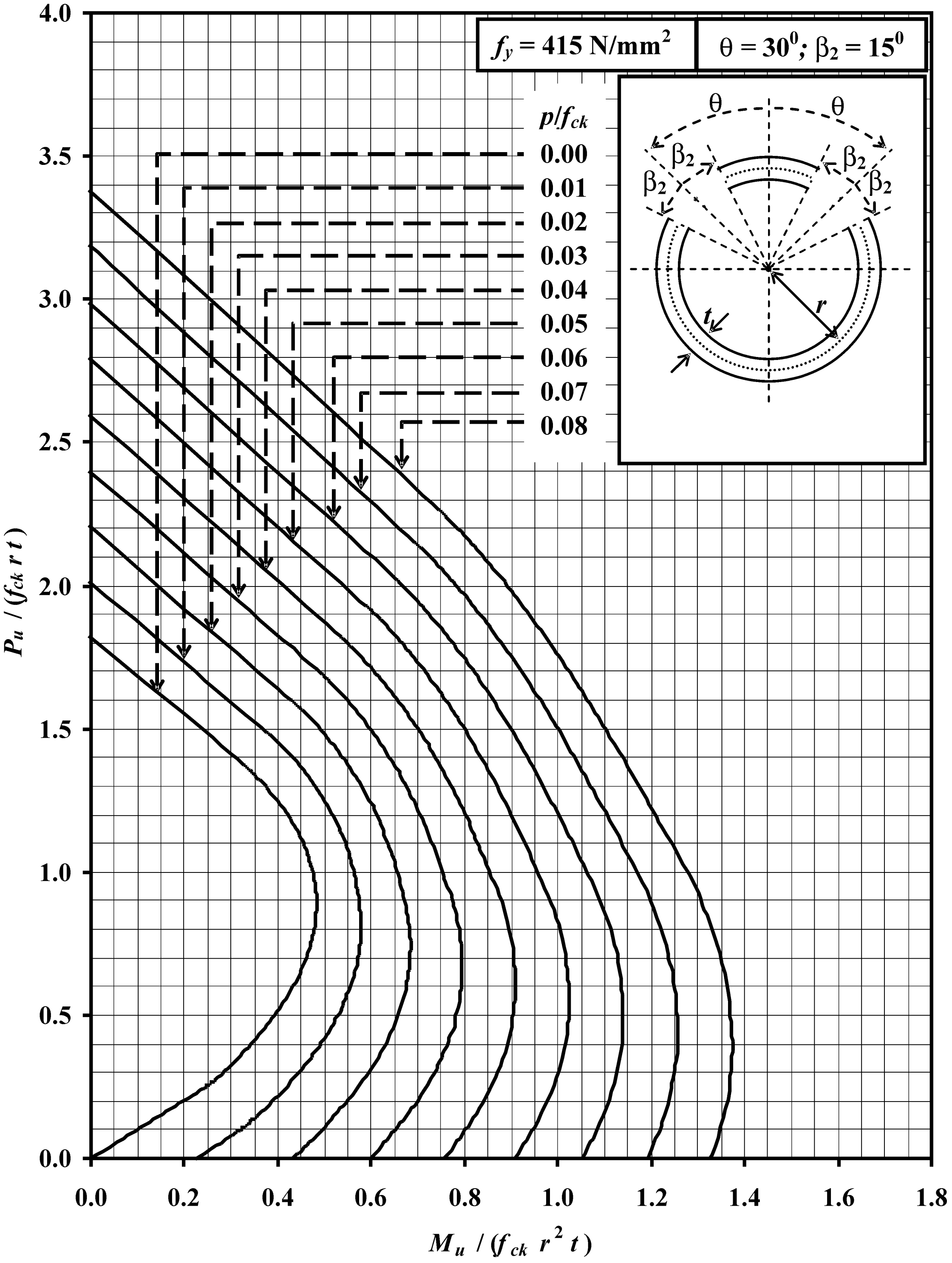


FIG. 9 INTERACTION DIAGRAM FOR SECTION WITH TWO OPENINGS

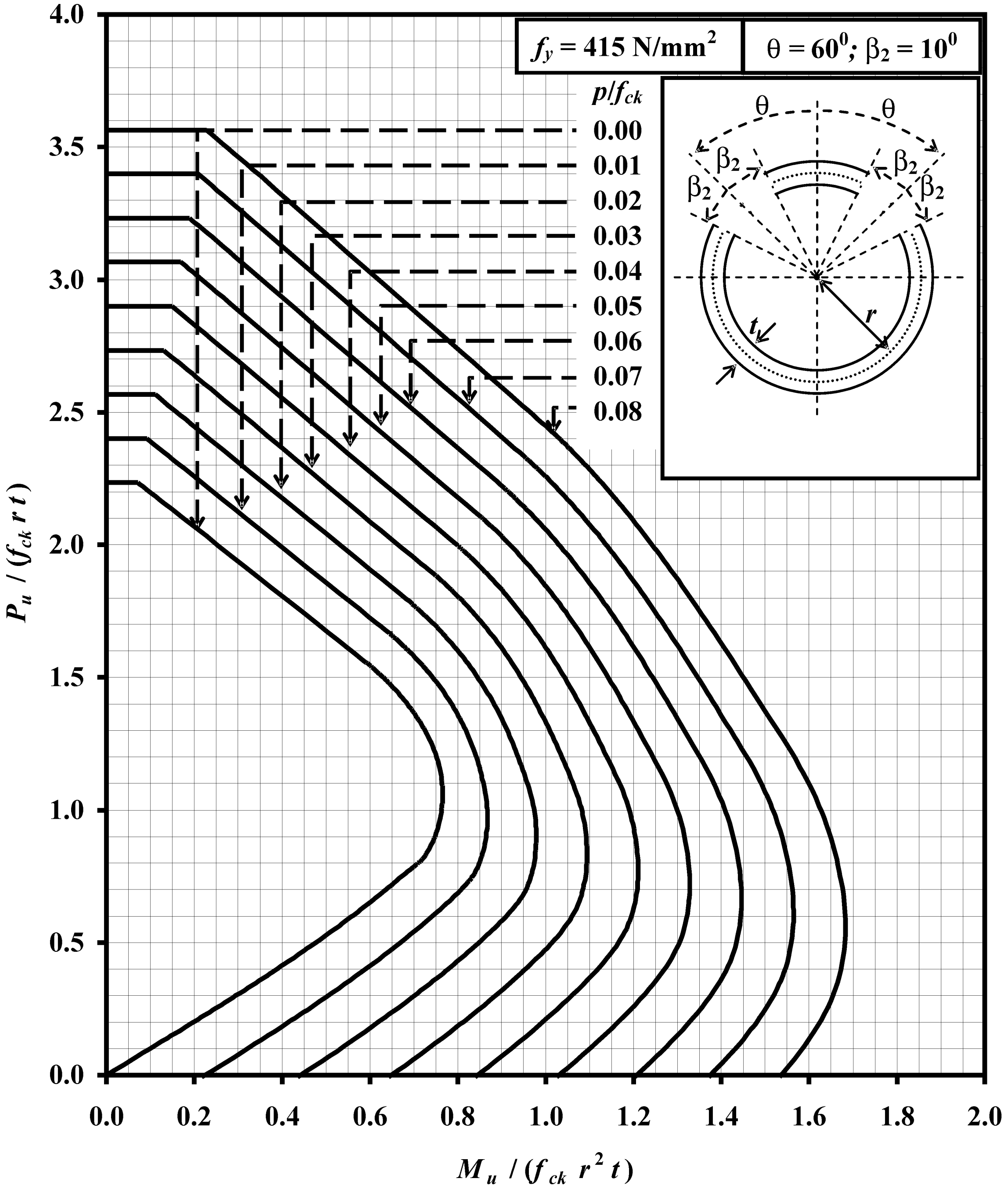


Fig. 10 Interaction Diagram for Section with Two Openings

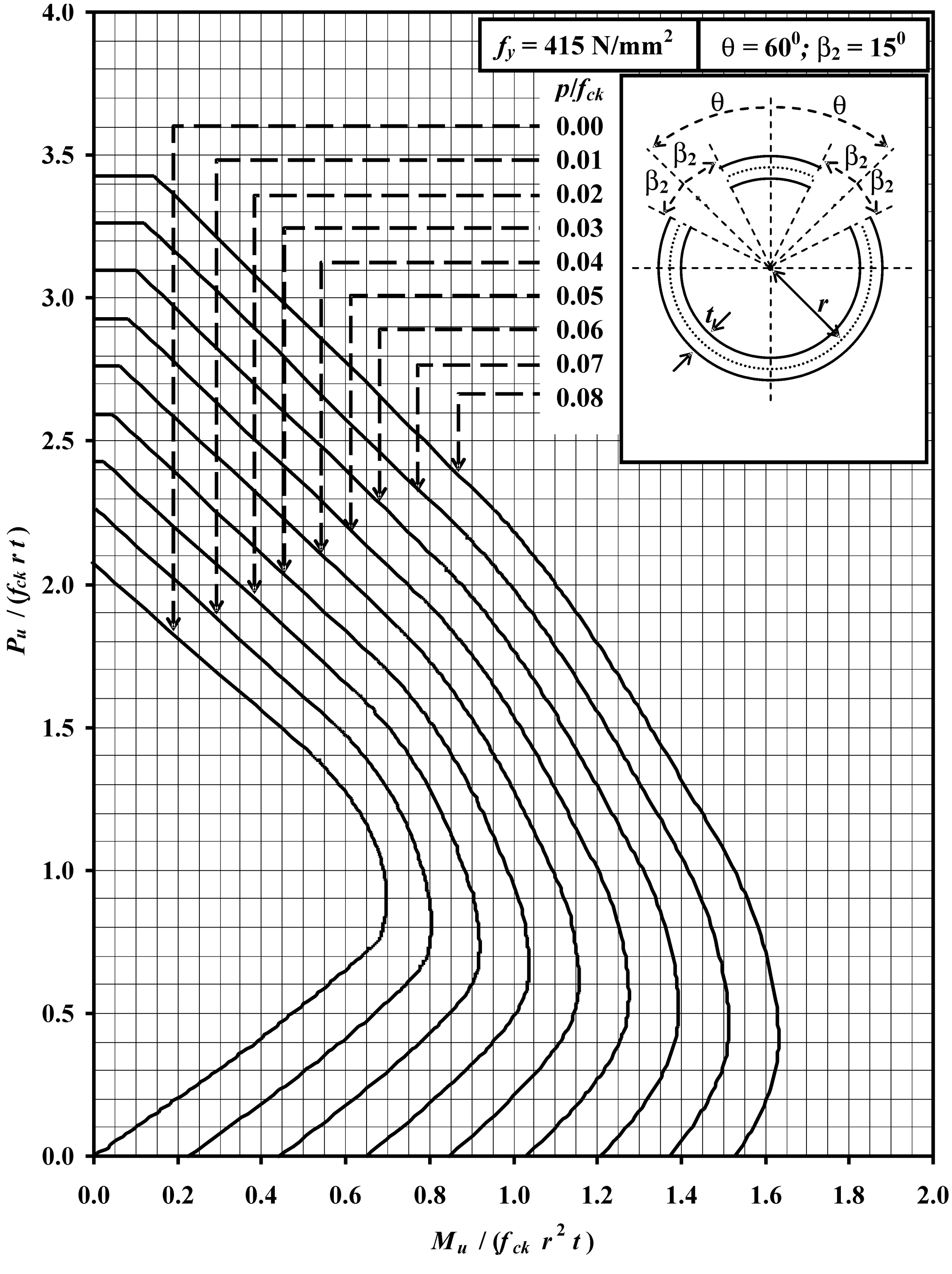


Fig. 11 Interaction Diagram for Section with Two Openings

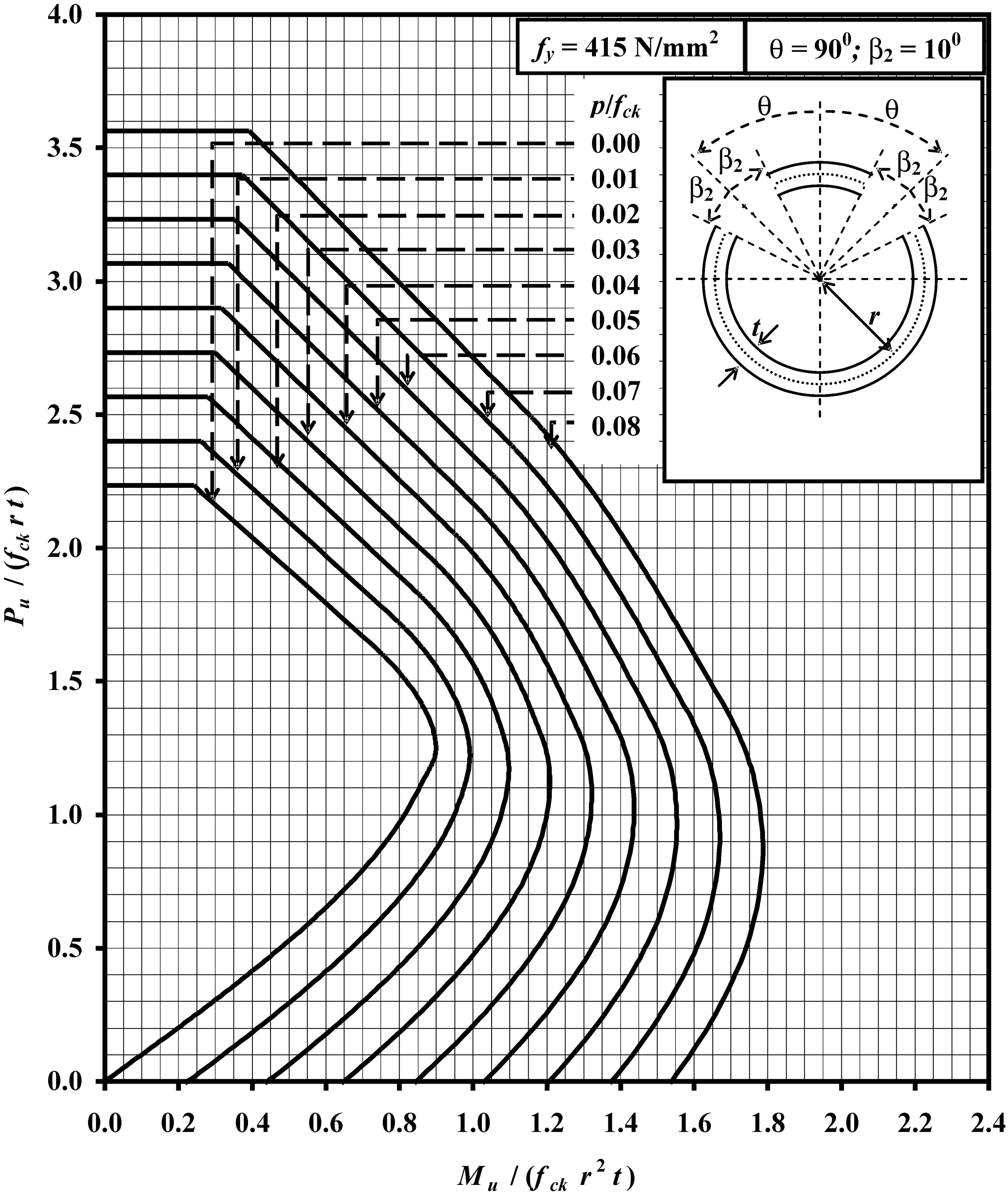


FIG. 12 INTERACTION DIAGRAM FOR SECTION WITH TWO OPENINGS

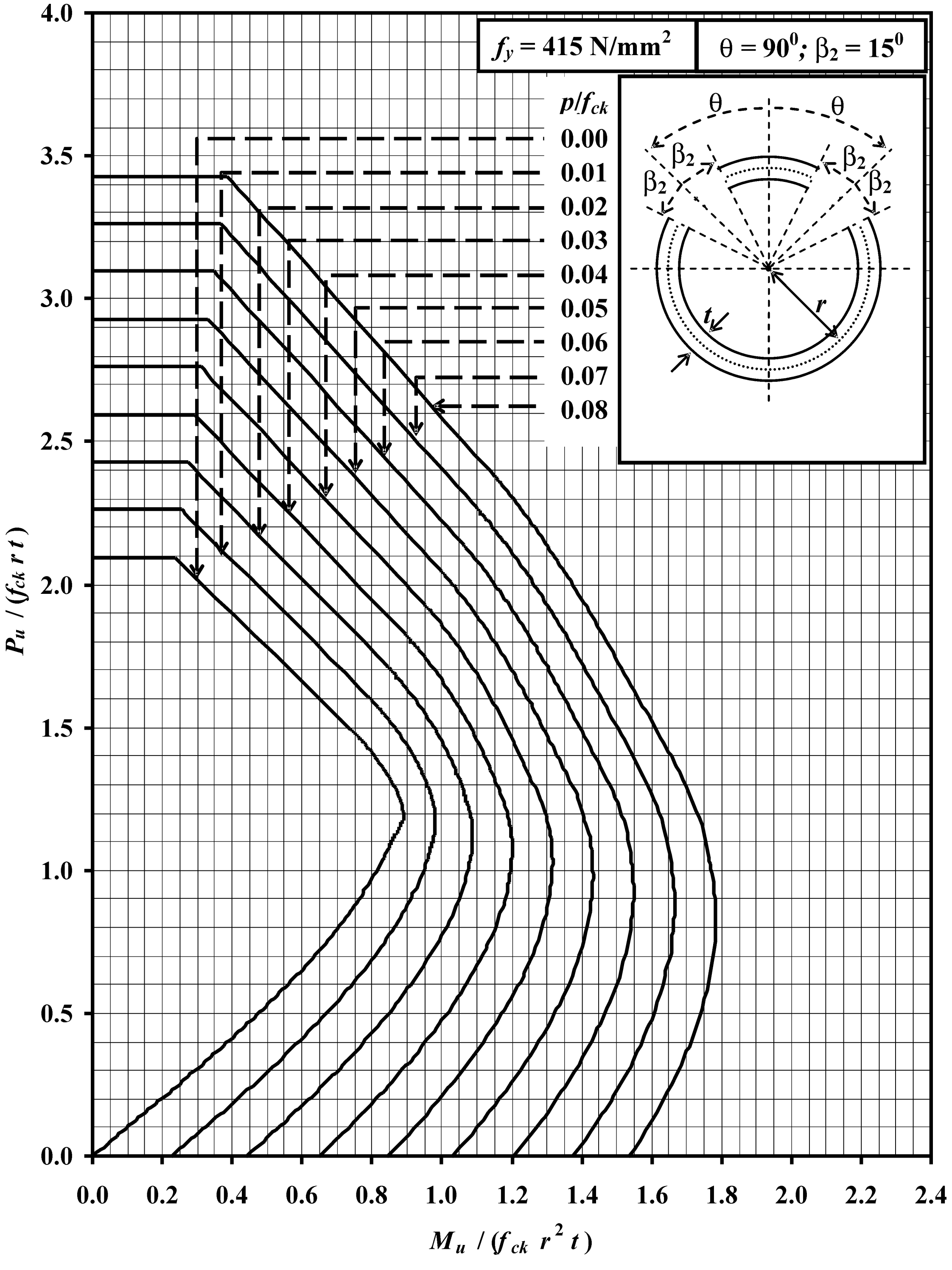


FIG. 13 INTERACTION DIAGRAM FOR SECTION WITH TWO OPENINGS

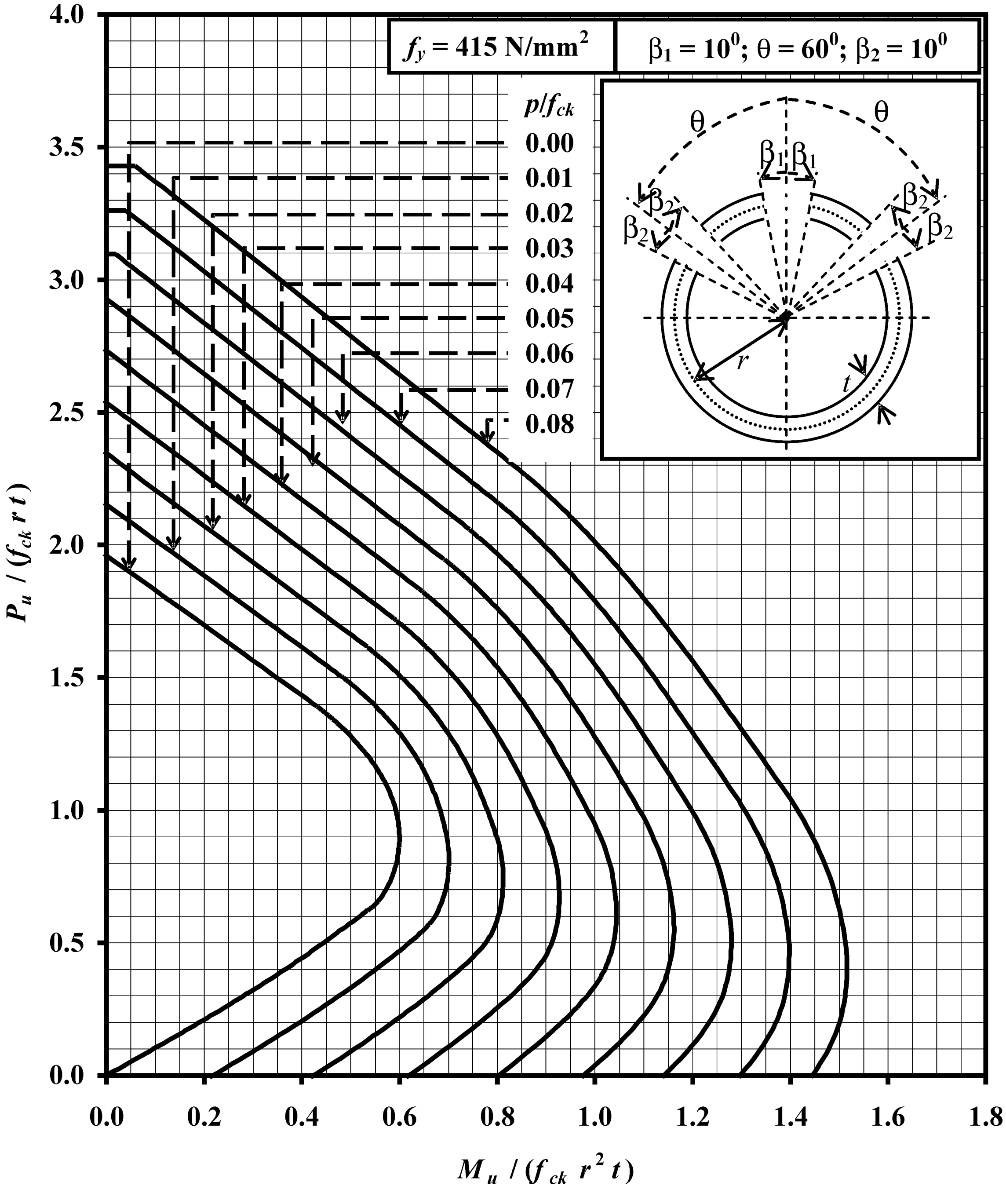


FIG. 14 INTERACTION DIAGRAM FOR SECTION WITH THREE OPENINGS

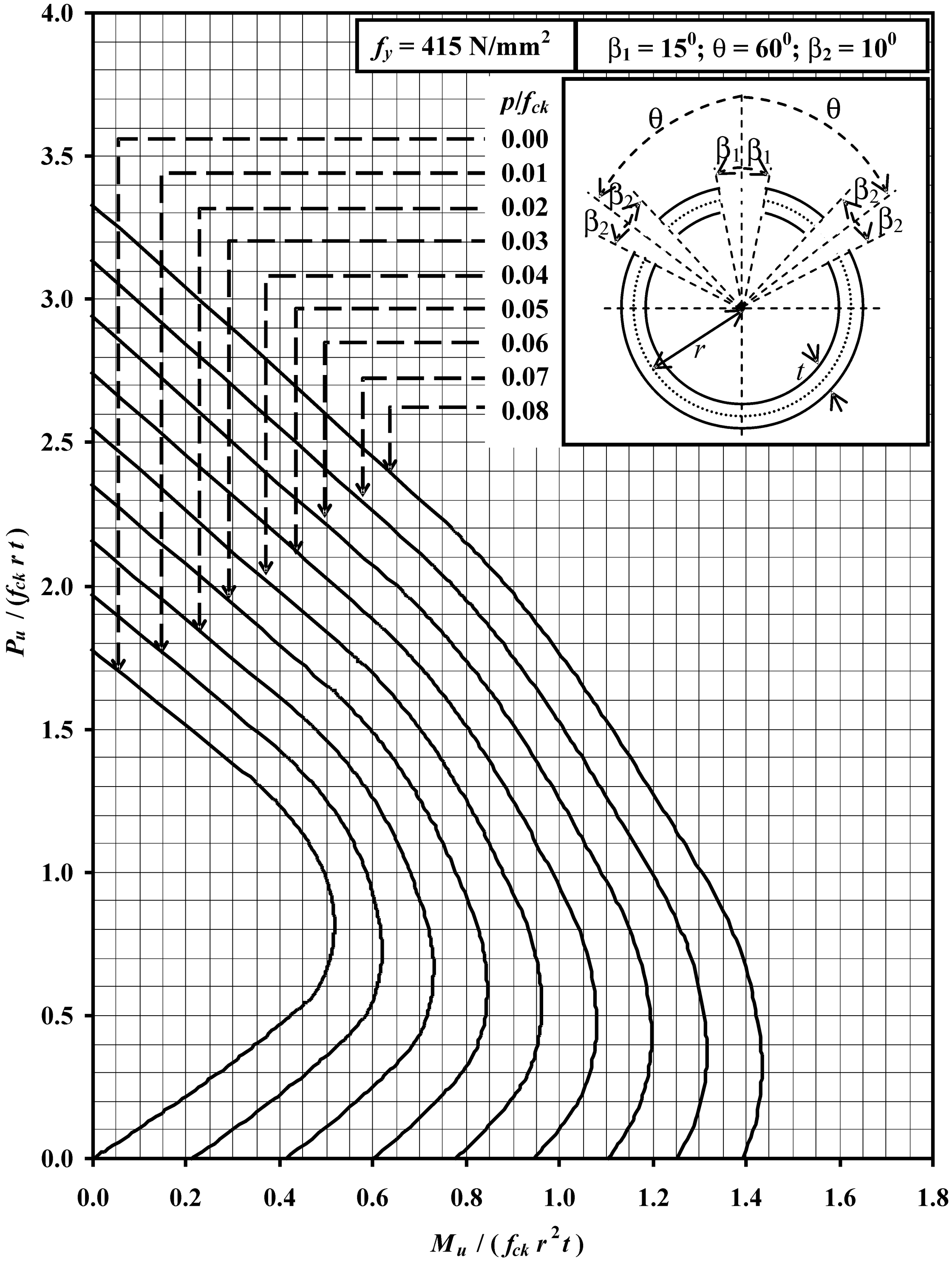


FIG. 15 INTERACTION DIAGRAM FOR SECTION WITH THREE OPENINGS

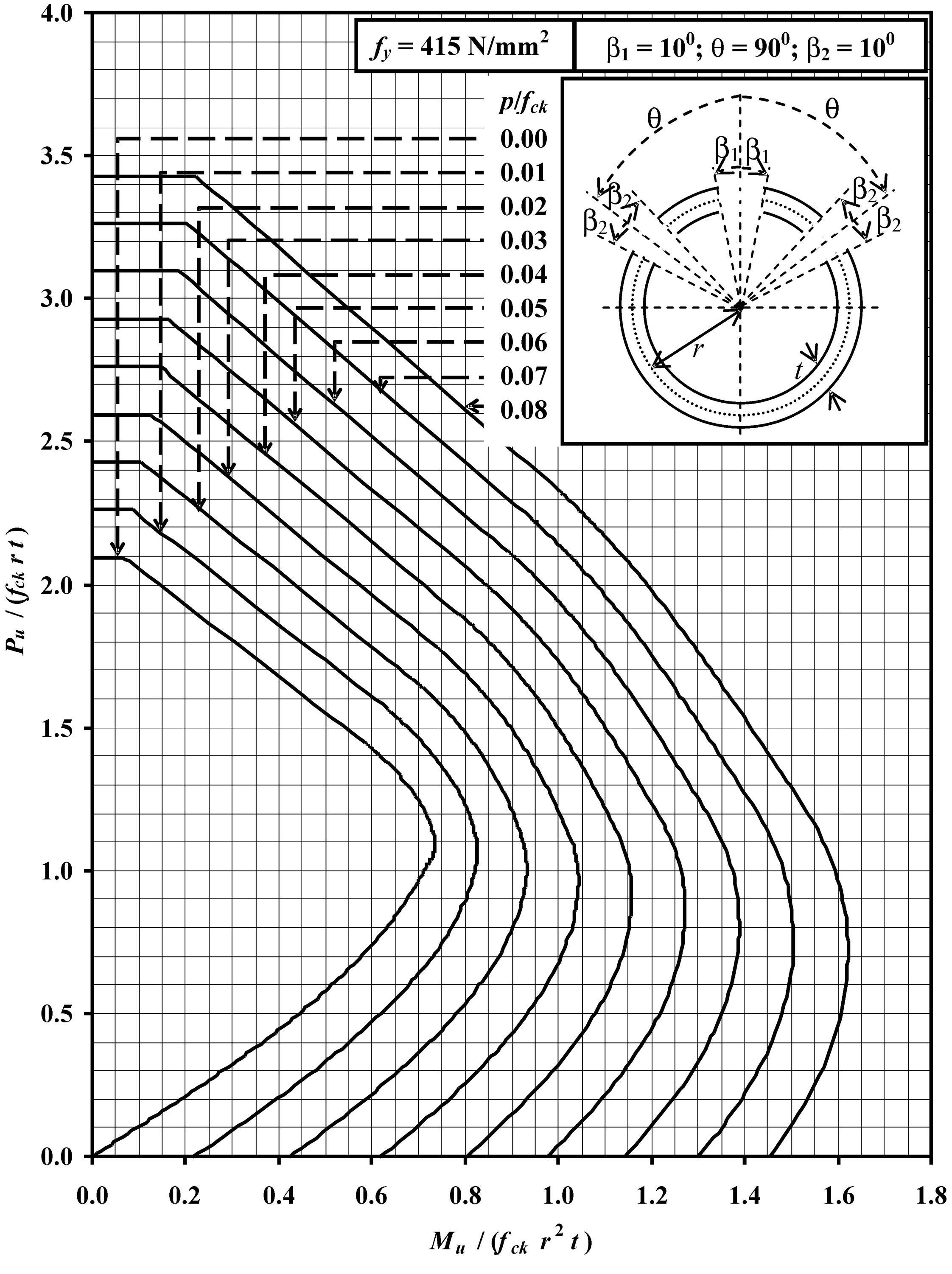


FIG. 16 INTERACTION DIAGRAM FOR SECTION WITH THREE OPENINGS

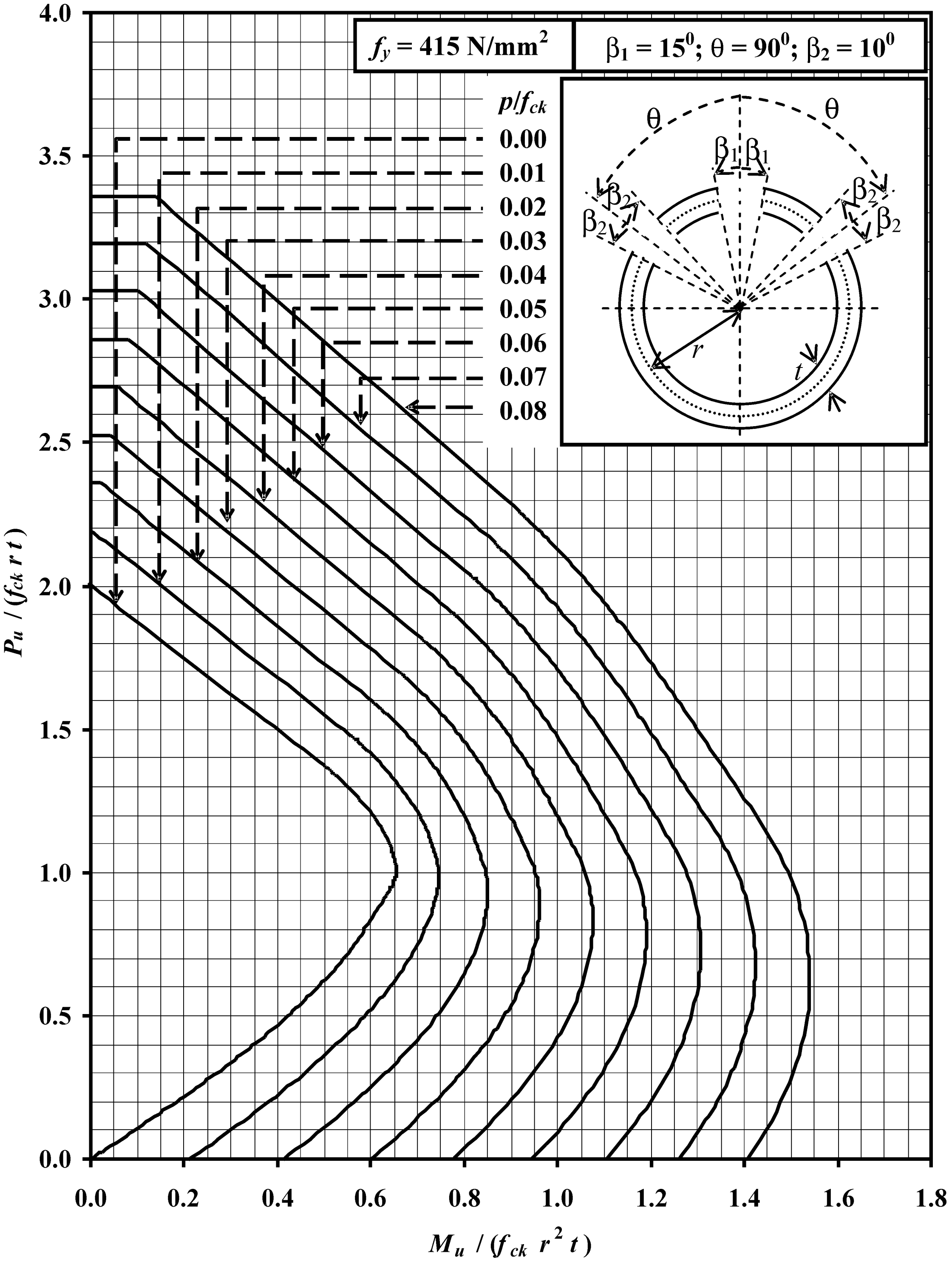


FIG. 17 INTERACTION DIAGRAM FOR SECTION WITH THREE OPENINGS

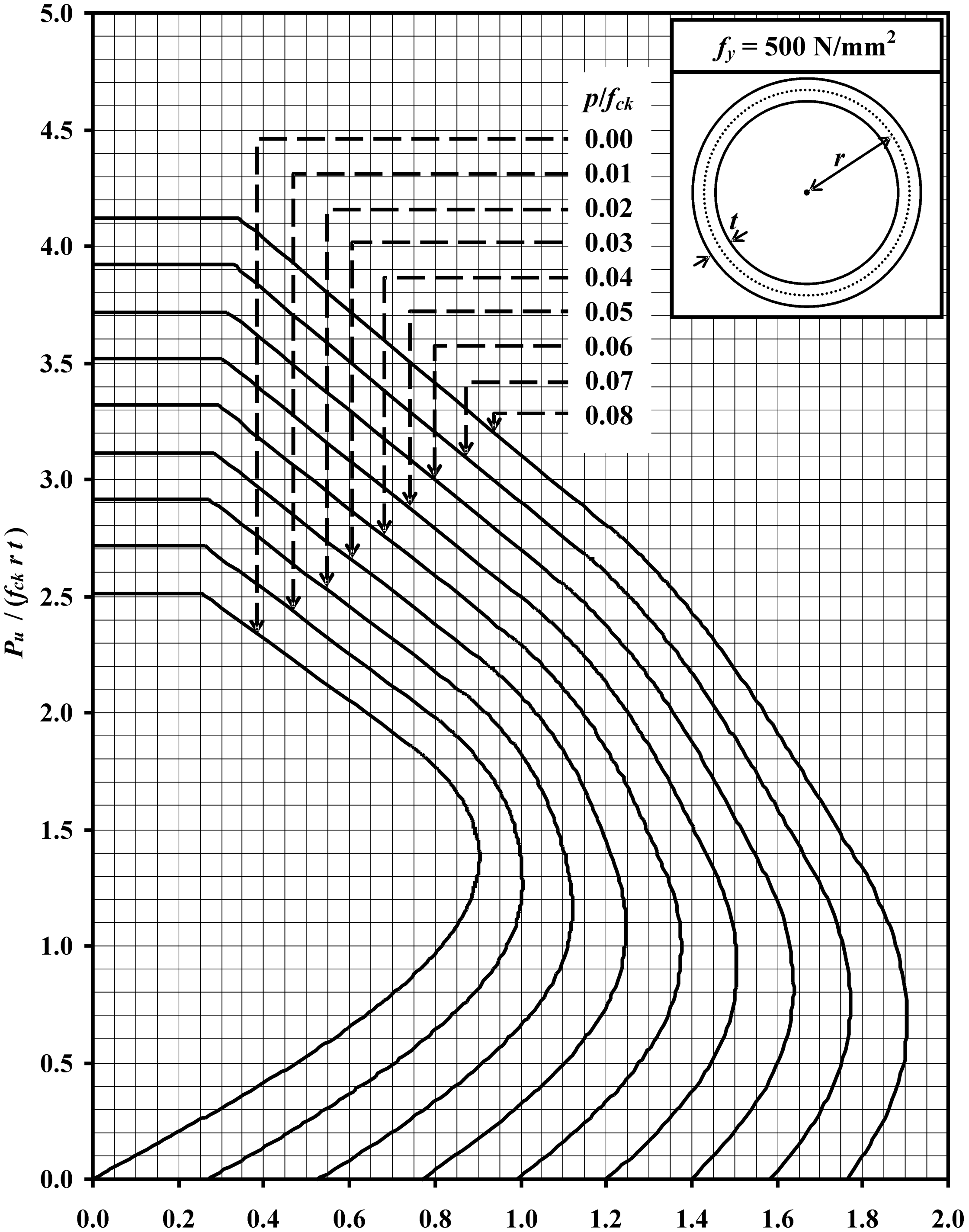


FIG. 18 INTERACTION DIAGRAM FOR SECTION WITHOUT OPENING

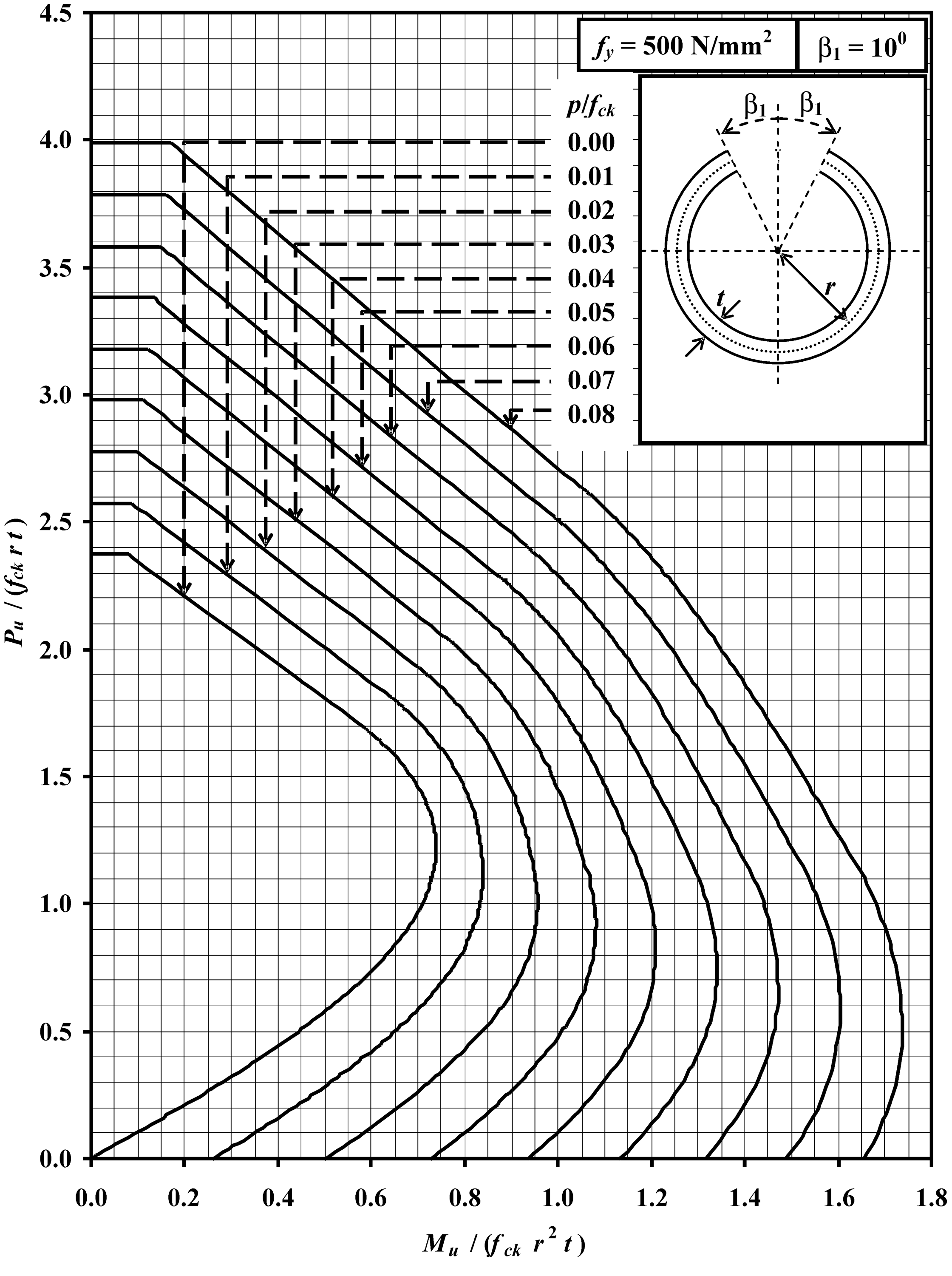


FIG. 19 INTERACTION DIAGRAM FOR SECTION WITH ONE OPENING

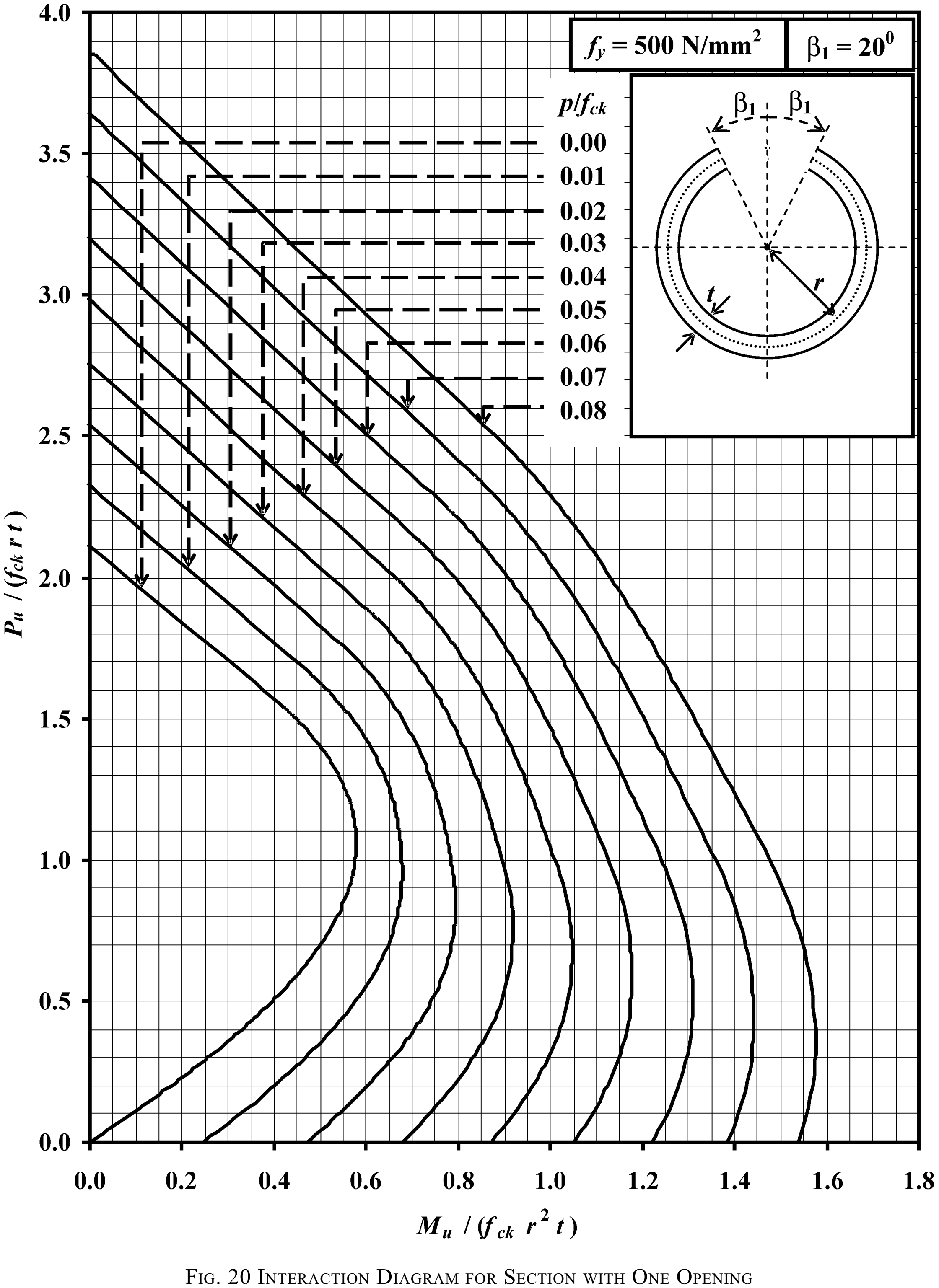


FIG. 20 INTERACTION DIAGRAM FOR SECTION WITH ONE OPENING

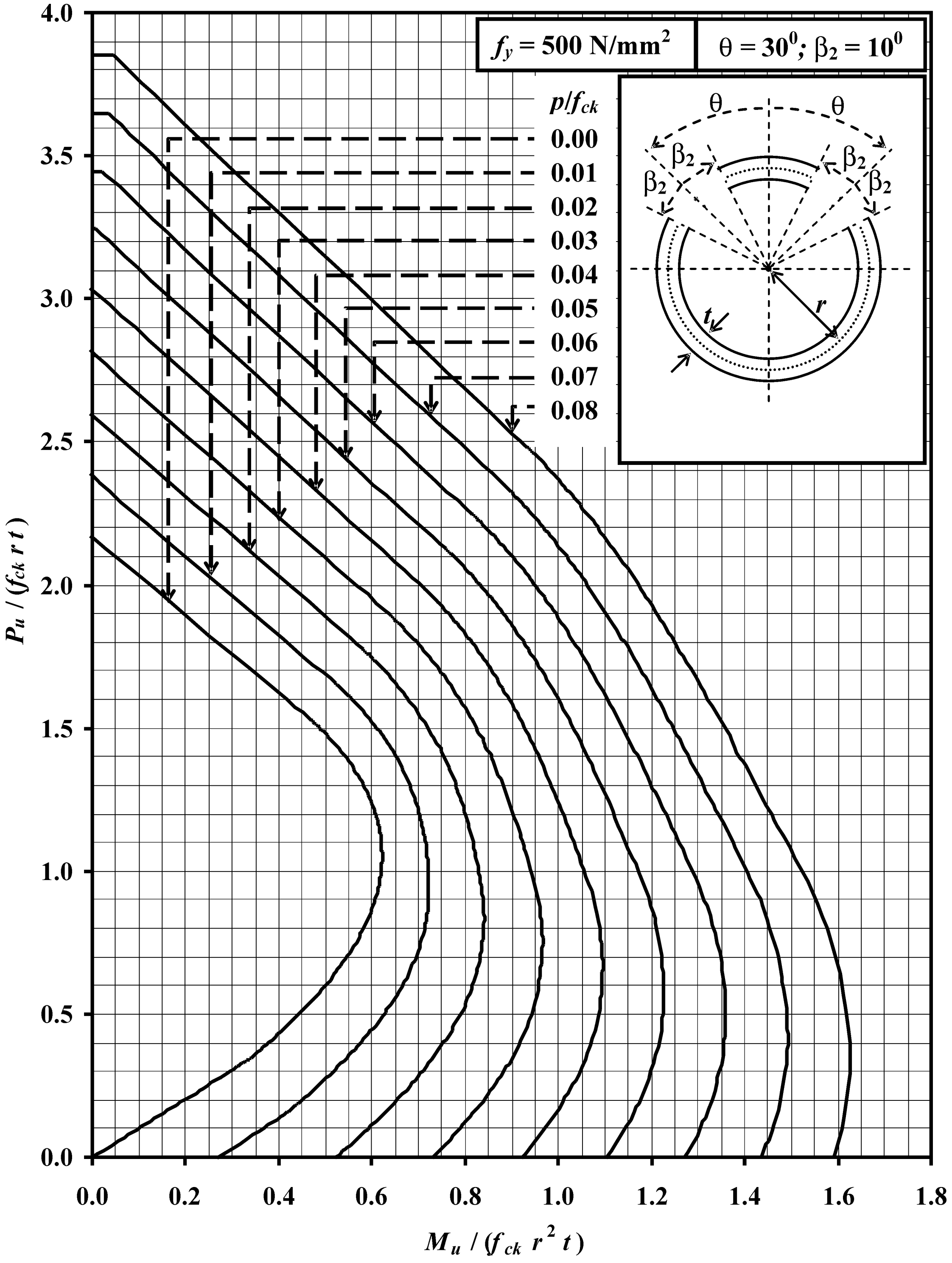


FIG. 21 INTERACTION DIAGRAM FOR SECTION WITH TWO OPENINGS

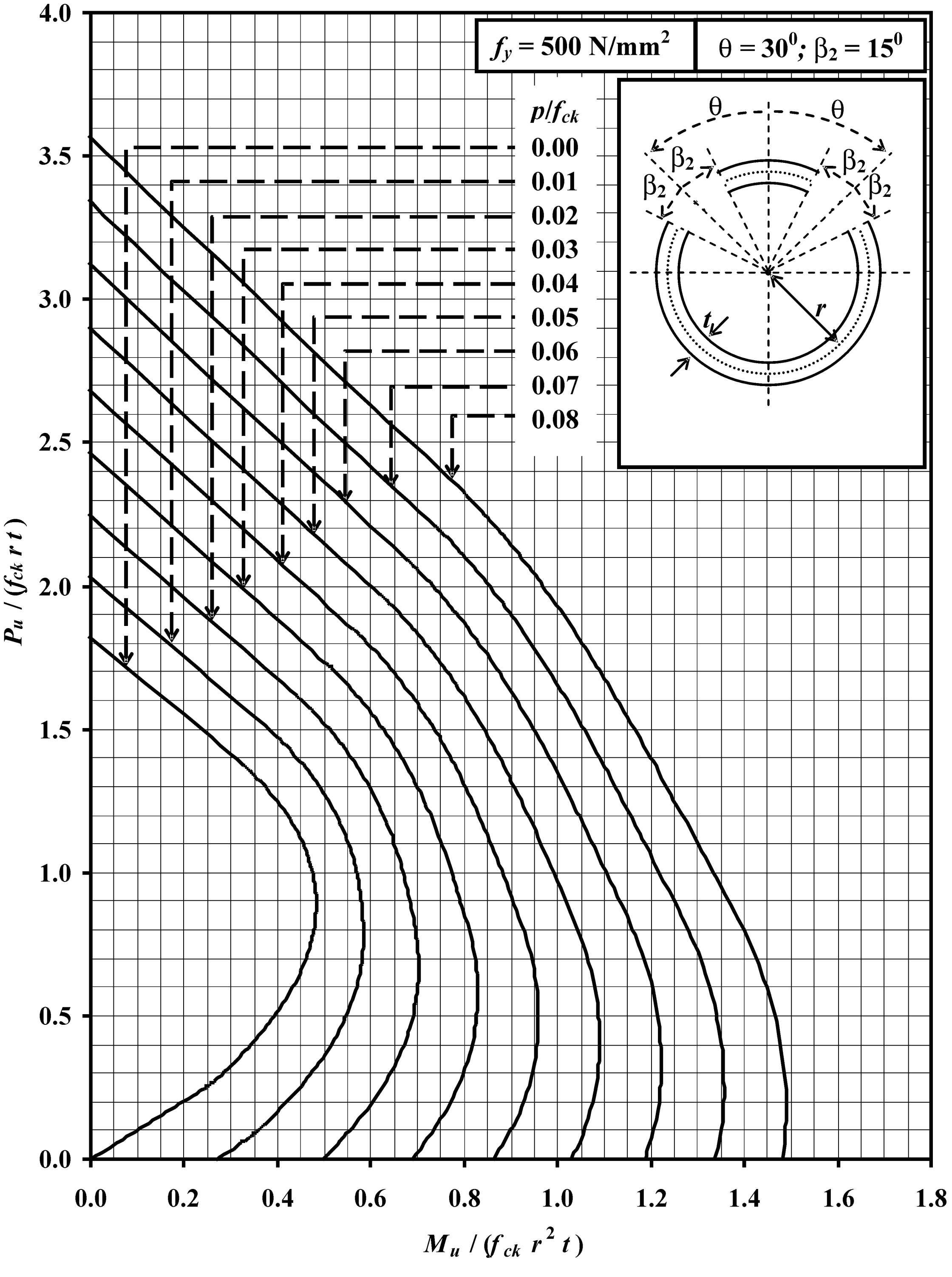


FIG. 22 INTERACTION DIAGRAM FOR SECTION WITH TWO OPENINGS

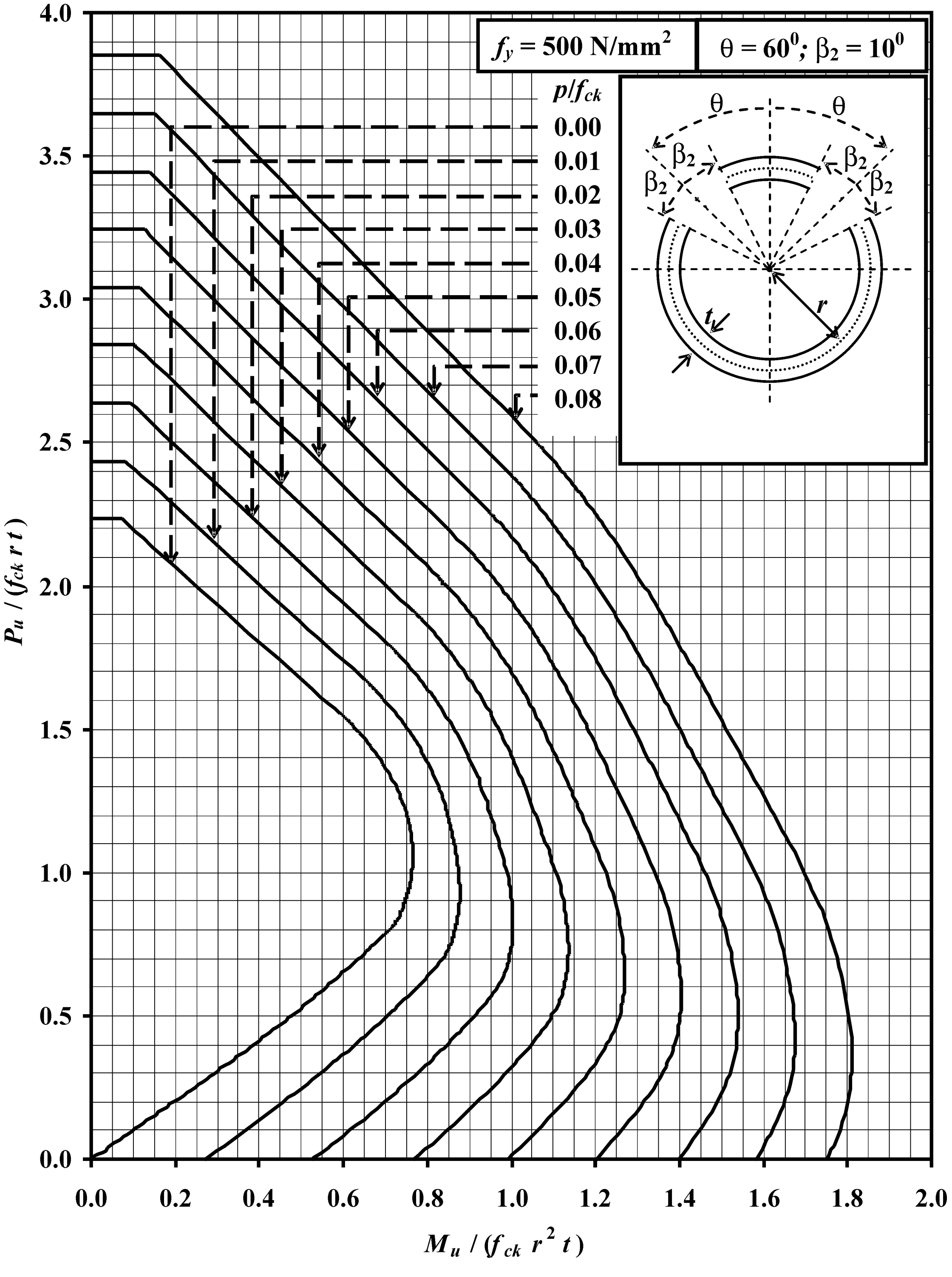


FIG. 23 INTERACTION DIAGRAM FOR SECTION WITH TWO OPENINGS

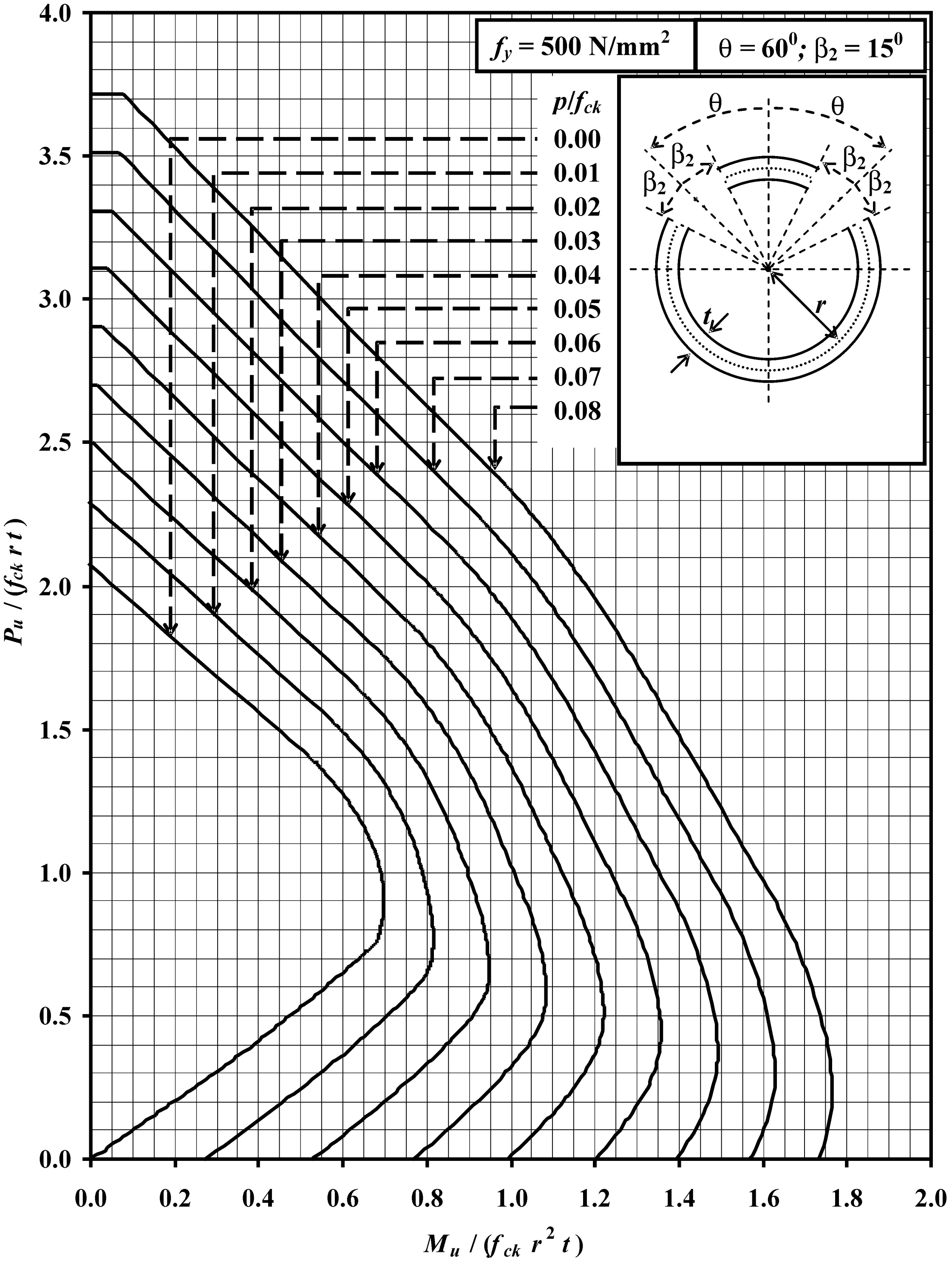


FIG. 24 INTERACTION DIAGRAM FOR SECTION WITH TWO OPENINGS

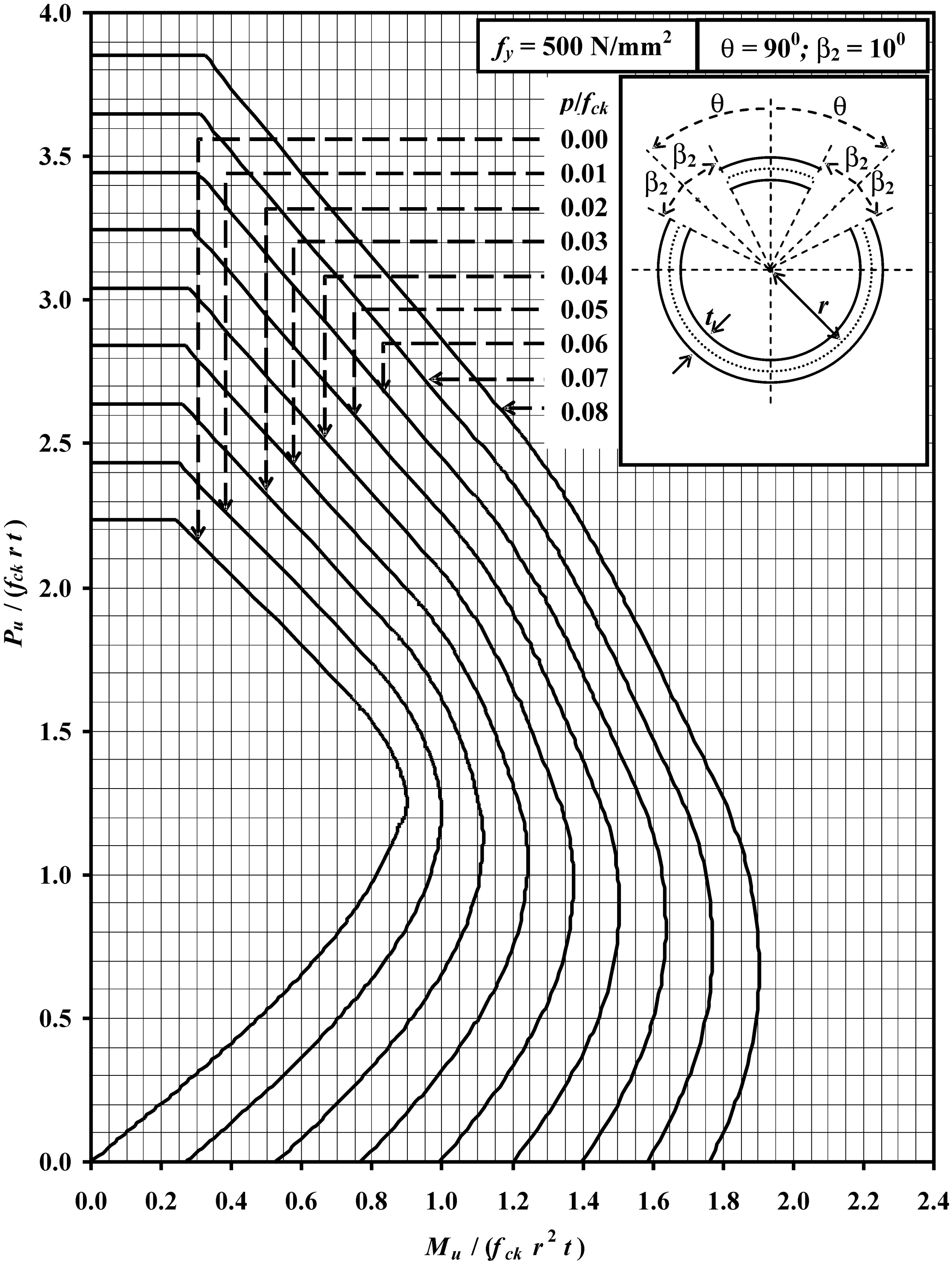


FIG. 25 INTERACTION DIAGRAM FOR SECTION WITH TWO OPENINGS

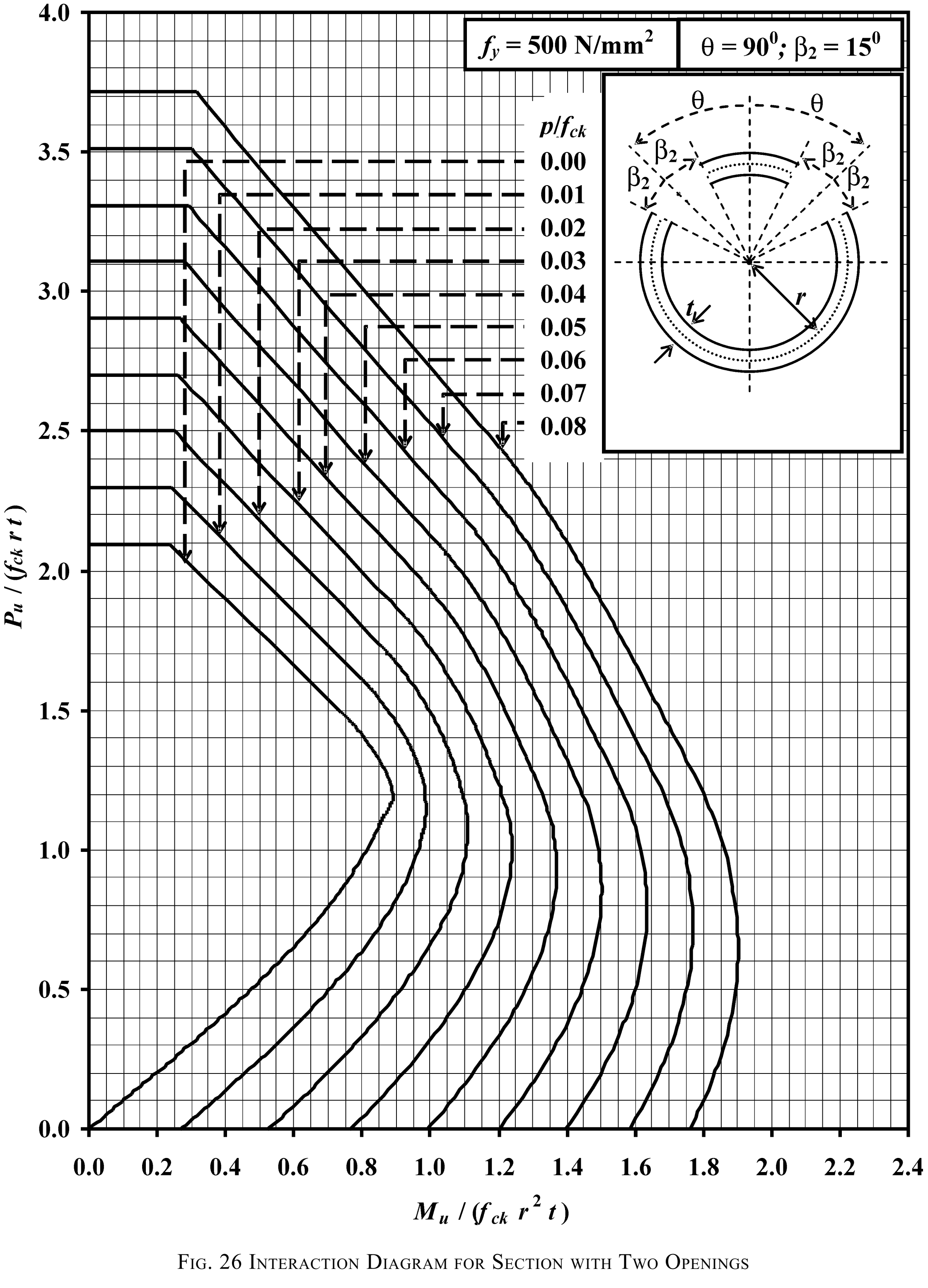


FIG. 26 INTERACTION DIAGRAM FOR SECTION WITH TWO OPENINGS

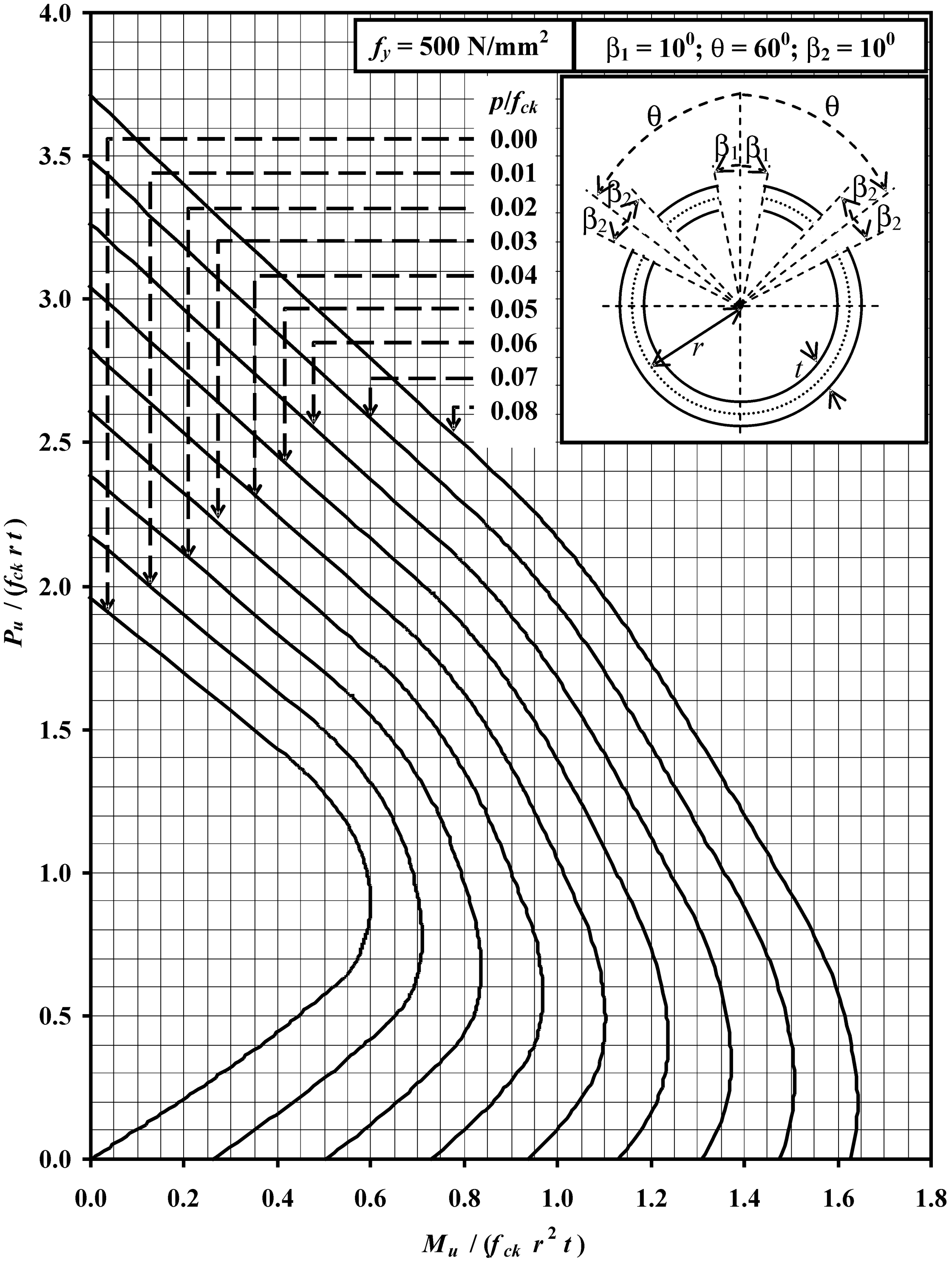


FIG. 27 INTERACTION DIAGRAM FOR SECTION WITH THREE OPENINGS

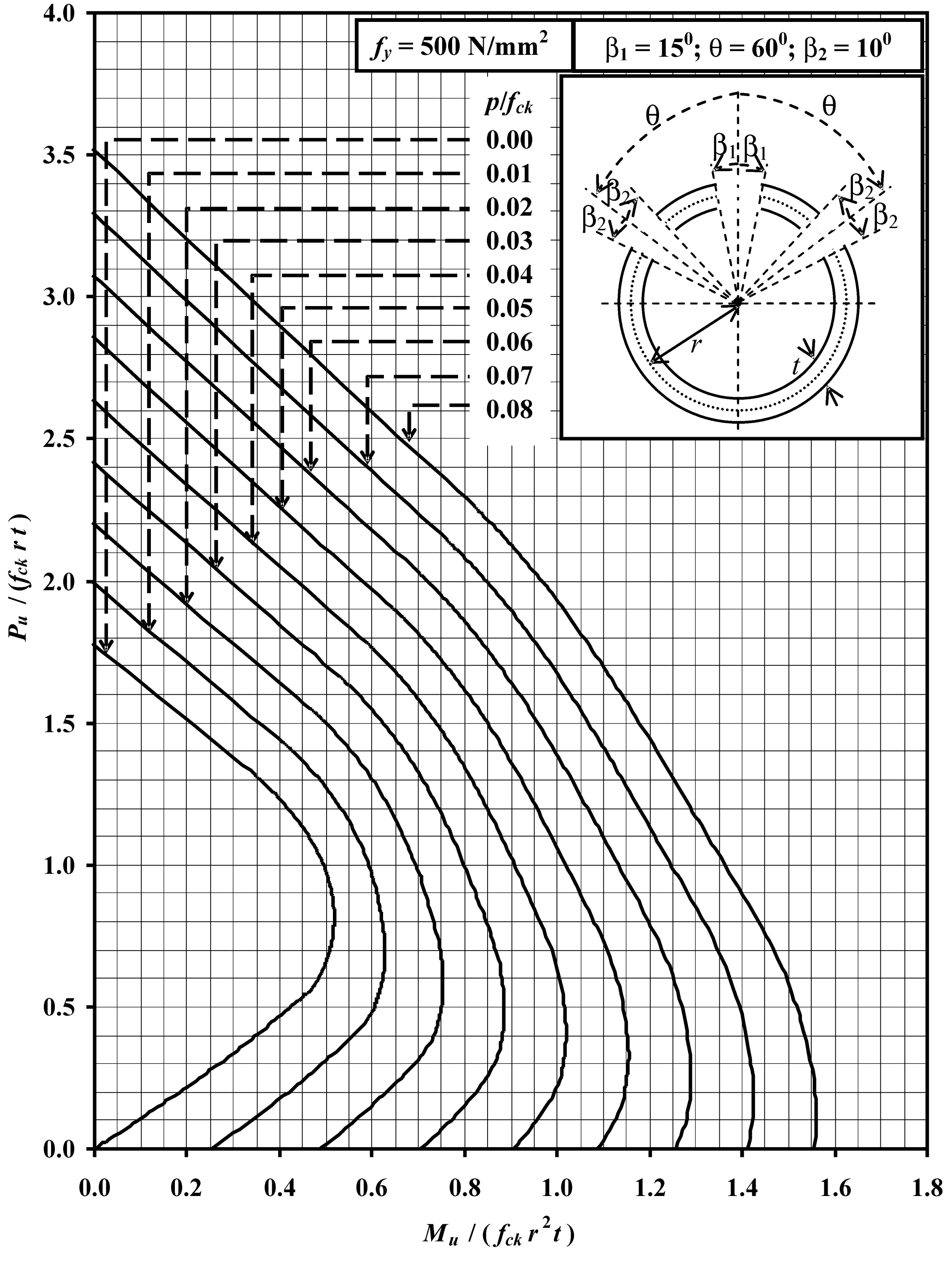


FIG. 28 INTERACTION DIAGRAM FOR SECTION WITH THREE OPENINGS

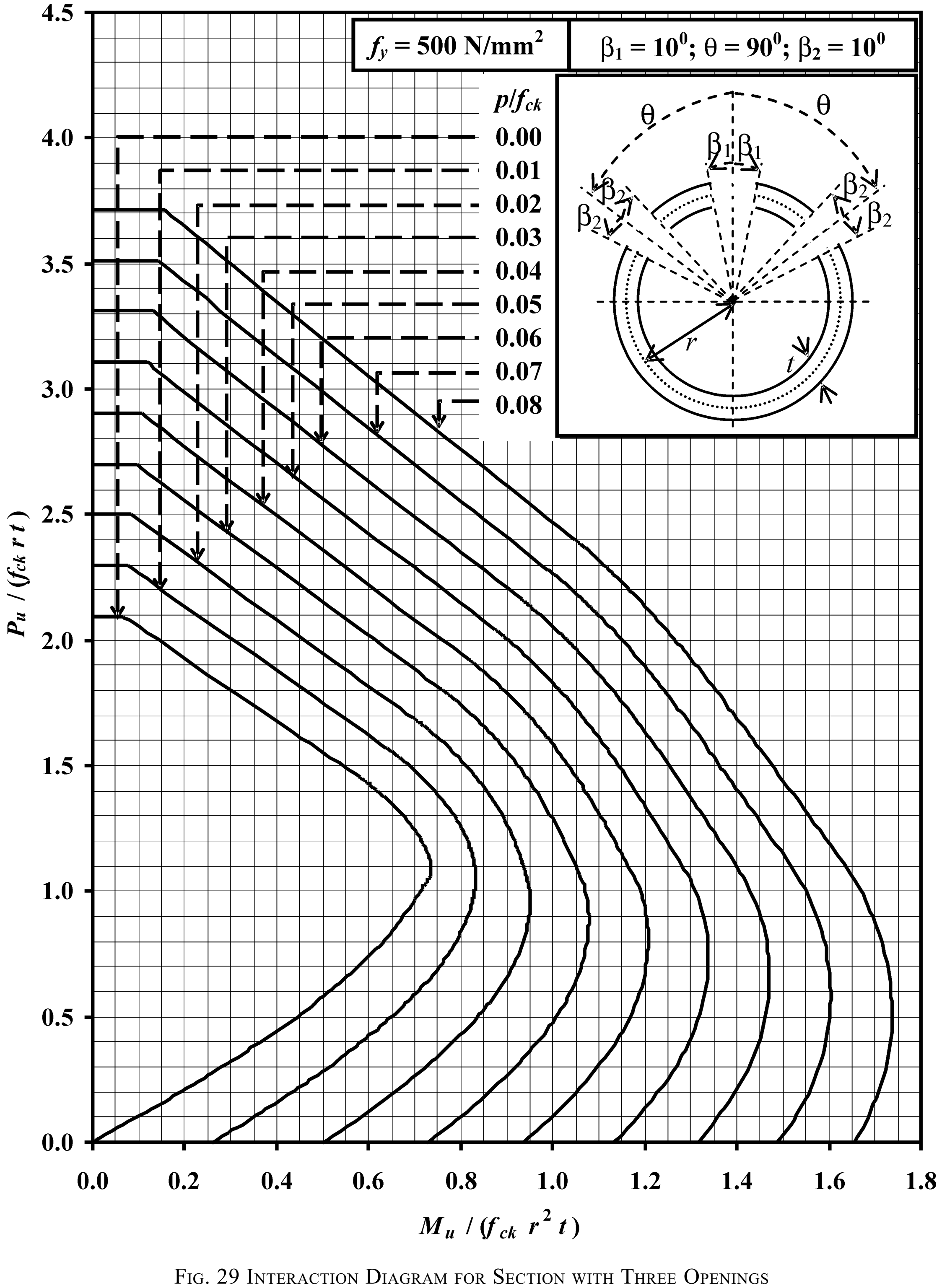


FIG. 29 INTERACTION DIAGRAM FOR SECTION WITH THREE OPENINGS

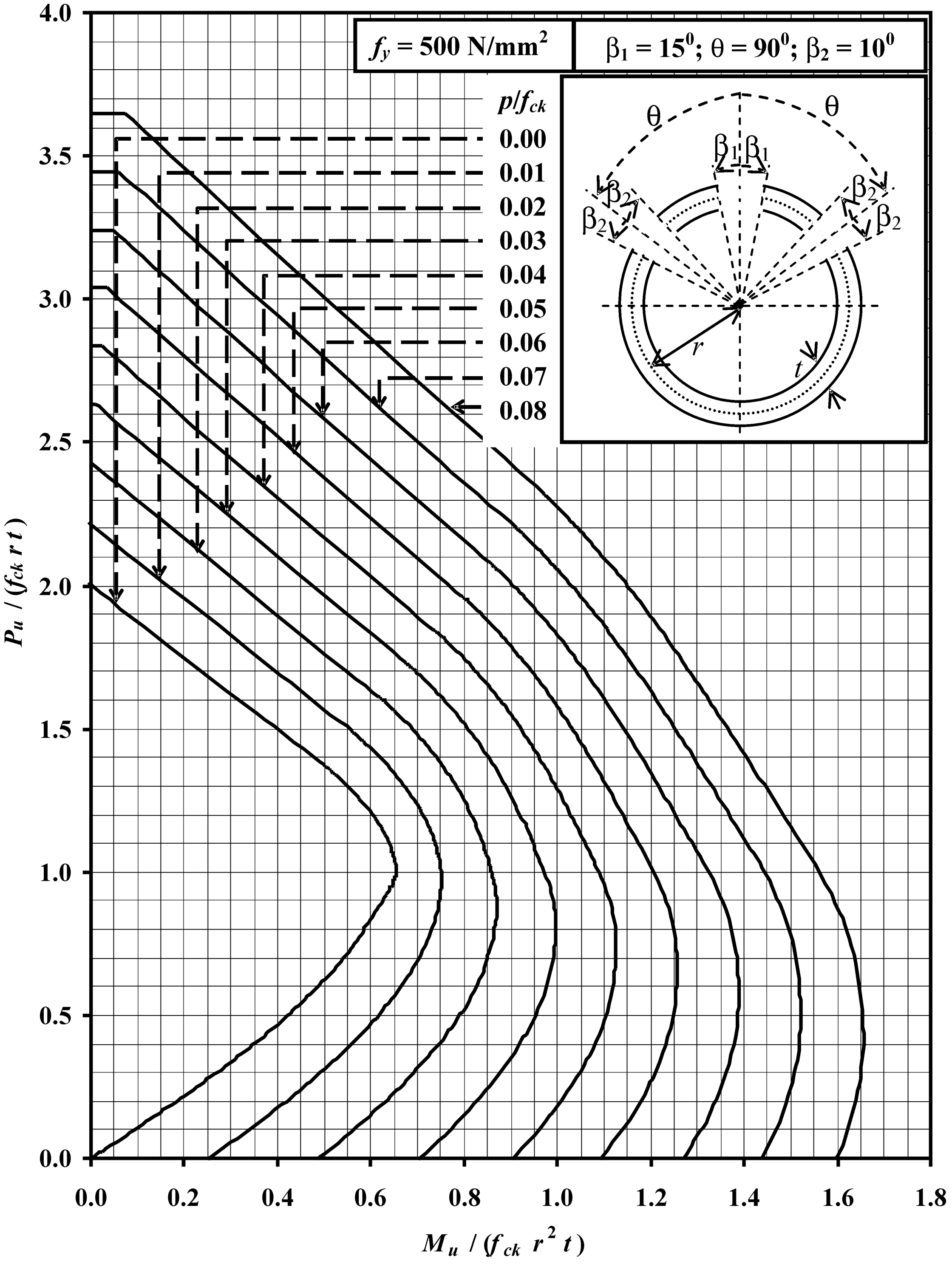


Fig. 30 Interaction Diagram for Section with Three Openings

ANNEX C

(*Foreword*)

DYNAMIC WIND LOADS ON CHIMNEYS

C-1 Dynamic wind loads are dominant loads in the structural design of tall Reinforced Concrete (RC) Chimneys of circular cross-section, which are one of the important power plant structures. From the aerodynamics point of view, the circular cross-section, although simple in its form, poses several challenges in the understanding of its flow behaviour, flow-structure interaction characteristics and hence in the prediction of the wind-induced aero-elastic response of a chimney. Significant advancements have been made during the past few decades all over the world towards scientific and rational assessment of loads, analysis, design concepts and methods of construction of chimneys. A chimney in an isolated condition is subjected to both (a) atmospheric buffeting effect due to turbulent velocity fluctuations in the approach flow contributing to along wind loads, and (b) vortex shedding and lateral component of the turbulence in the approach flow contributing to across-wind loads. Since wind speed varies randomly both in time and space, the analysis of wind loads is based on the principles of statistics and theory of random vibrations. The mean along-wind load per unit height, at any given height, is estimated by multiplying the design wind pressure due to hourly mean wind speed at that height with the mean drag coefficient and outer diameter. The Gust Response Factor (GRF) method, originally developed by Davenport, and modified later by Vickery for the computation of along-wind loads / response of a chimney is widely recognized and being used in most of the international codes and hence the same method is recommended in this standard.

The estimation of across-wind loads, due to vortex shedding is relatively a more complex issue. The challenges which retard the better understanding of the behaviour of chimney are due to: (a) the effect of Reynolds number and the turbulence intensity on the aerodynamic parameters such as mean and fluctuating drag and lift coefficients, Strouhal number, correlation length, wake pressure characteristics, etc; (b) proper extrapolation of boundary layer wind tunnel experimental results to full-scale chimney conditions; (c) limited information from full-scale measured data on various aerodynamic parameters with considerable scatter, etc. Despite the above, concerted research efforts are still being undertaken in India and elsewhere to develop improved predictive models on the response of chimneys subjected to across-wind loads. Although a complete understanding of the across-wind response of a chimney due to vortex shedding is presently not available, the semi-empirical method developed by Vickery and his coworkers is regarded as most satisfactory method and it is included in the international codes of ACI 307-08 and CICIND. For this reason, the method that is in line with ACI 307-08 is recommended in the present standard.

In the structural design provisions, the philosophy of limit states design is adopted in this standard, in line with international practice.

ANNEX D

(*Foreword*)

COMMITTEE COMPOSITION

Special Structures Sectional Committee, CED 38

Organization	*Representative(s)*
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Bharat Heavy Electricals Limited, New Delhi	Shri Hemant Malhotra Shri Anand Narayan (*Alternate*)
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In personal capacity (*Director, Wind Engg. Applications Centre, JUET, Guna, Madhya Pradesh*)	Dr S. Arunachalam (***Convener***)
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(*Continued from Second Cover*)

Srinivasa Rao, P. and Devdas Menon, (1995), 'Ultimate Strength of Tubular RC Tower Sections under Wind Loading', Indian Concrete Journal, 69,117-123.

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Chu, K. and Afandi, O.F., (1966), 'Analysis of Circular and Annular Slabs for Chimney Foundations', Journal of the American Concrete Institute, Title No. 63-63, Vol. 63, No. 12, pp. 1425-1447.

Information about dynamic wind loads on chimneys is given at Annex C.

The composition of the Committee responsible for the formulation of this standard is given in Annex D.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of specified value in this standard.

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Amendments Issued Since Publication

Amend No.	Date of Issue	Text Affected

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